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Ministry of the Environment

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Water Resources Report 5d

A Hydrogeological Study along the North Shore of Lake Ontario in the Bowmanville-Newcastle Area

IFYGL

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Ontario

WATER RESOURCES
REPORT 5d

A Hydrogeological Study along the North Shore of Lake Ontario in the Bowmanville-Newcastle Area

By
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WATER QUANTITY MANAGEMENT BRANCH
River Basin Research Section

TORONTO ONTARIO

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

MAPS
(in back pocket)

FOREWORD

Part of the contribution of the Ontario Ministry of the Environment to the International Field Year for the Great Lakes program is the estimation of the amount of ground-water inflow to Lake Ontario from the Canadian side, by extrapolating data from selected areas representative of large hydro-geologic regions. This report which describes the hydrogeology of the Bowmanville-Newcastle area is the first in a series of several reports dealing with the ground-water regimes of seven selected representative areas along the shoreline of Lake Ontario. A final report will be compiled summarizing the findings of all seven studies.

Figure 1a. Location of the IFYGL Bowmanville study area in southern Ontario.

A HYDROGEOLOGICAL STUDY ALONG THE NORTH SHORE OF LAKE ONTARIO IN THE BOWMANVILLE-NEWCASTLE AREA

INTRODUCTION

The hydrogeological regimes of selected areas, considered to be representative of larger hydrogeologic regions, have been studied during the International Field Year for the Great Lakes (IFYGL) program by the Ontario Ministry of the Environment (MOE). The north shore of Lake Ontario in the Bowmanville-Newcastle area is considered to be representative of the ground-water regime developed in the hydrogeologic region extending from Oshawa to the Trent River (approximately 70 miles). The purpose of this study was to determine the amount of ground-water flow into Lake Ontario within the Bowmanville-Newcastle area. The obtained results from this study and from similar studies in other representative areas will be used to assess the role of ground water in the hydrologic budget of the Lake Ontario drainage basin.

Field investigations were made of the surficial geology, streamflows and ground-water levels in the study area. Aerial photographs obtained from the Ministry of Natural Resources were used to supplement the field studies. Samples from the surficial deposits in the area were analyzed to determine their grain-size distribution and carbonate composition. Data from automatic water-level recorders on a number of deep observation wells and periodic water-level measurements (once or twice a month) in abandoned shallow wells were made available through the International Hydrological Decade (IHD) program of the Ministry. Hydrographs of streamflows for the Bowmanville and Wilmot creeks were separated into direct runoff and baseflow to obtain estimates of ground-water discharge. Additional hydrogeologic information from existing water-well records on file with the MOE and supplied by water-well drillers was assembled.

Previous Work

Information on the Pleistocene deposits in the study area was published by Wilson (1905 and 1908), Coleman (1909, 1932 and 1936), Keele (1924), Chapman and Putnam (1951), Gravenor (1957), and Singer (1973).

The stratigraphy of the bedrock underlying the study area has been described by Chapman and Putnam (1951), Liberty (1955, 1969) and Beards (1967).

Two reports by Barouch (1971) were published by the Ontario Water Resources Commission. The first report deals with hydrograph separation in the Wilmot Creek basin using recession factor analysis and chemistry of streamflow and the second report evaluates the ground-water storage capacity in the Soper Creek sub-basin using the physical parametric approach.

Acknowledgements

Sincere appreciation is expressed to R. C. Ostry whose advice during the study proved invaluable and to other staff of the River Basin Research Section for their field and office assistance.

The author wishes to acknowledge the co-operation of the Ontario Hydro-Electric Power Commission for making records of their test holes in the Raby Head area available. Thanks are also due to the St. Mary's Cement Company which provided available geological data.

Appreciation is expressed to the residents of the area who kindly permitted the use of abandoned wells on their properties as observation wells.

GEOGRAPHY

Location

The study area is bounded on the south by the present-day shore of Lake Ontario and on the north by the bluffs of the abandoned Lake Iroquois shoreline. The area extends east and west beyond the watershed divide of the Bowmanville, Soper and Wilmot creeks drainage basin from longitude 78° 30′ W to longitude 78° 45′ W (Figure 1b). Portions of the townships of Darlington and Clarke in the County of Durham are contained within the study area. There are three main population centers in the area, the Town of Bowmanville, the Village of Newcastle and the Police Village of Orono. On January 1, 1974, the study area became part of the Town of Newcastle within the Regional Municipality of Durham.

Physiography

After the retreat of the last glacier, the present Lake Ontario basin was occupied by a glacial Lake Iroquois. The study area is a part of the Iroquois Plain and was described by Chapman and Putnam (1951) and designated as one of the major physiographic regions of southern Ontario. The Iroquois shoreline lies from 2 to 8 miles north of the present day shoreline of Lake Ontario and is tilted upwards to the northeast. The elevation of the Iroquois shoreline is approximately 515 feet at the western end of the study area, increasing gradually to reach approximately 535 feet at its eastern end. The rolling surface of the Iroquois Plain reflects the topographic expression of the underlying till plain.

In general, the study area slopes down from the north toward Lake Ontario. The land surface along the shore of Lake Ontario rises abruptly as bluffs above the level of the lake which stands at an elevation of approximately 244 ± feet above the mean sea level (msl). The bluffs diminish to only a few feet in height near the mouths of major streams entering the lake and reach a maximum height of over 140 feet to the southeast of the Village of Newcastle.

The highest elevation is over 690 feet above msl at the top of a drumlinoid hill in the eastern end of the study area. Gravel bars found at the southern base of this hill and similar adjacent hills suggest that these were islands in Lake Iroquois. A number of hills with crest elevations of less than 430 feet are found in the western end of the study area.

Ground-Water Discharge Effects

Ground-water discharge, in the form of springs or seepage faces from permeable beds, plays a major role in reshaping the morphology of the bluffs. Discharging ground water can carry a considerable quantity of sand and in effect undermine any overlying material. Bird and Armstrong (1970), in describing the role of ground water on the recession of the Scarborough Bluffs, noted that the presence of subsurface water has the effect of increasing the unit weight of the soil and decreasing the effective stress. Both these factors contribute to reducing the slope stability. As the quantity of ground water increases, the resulting lubrication and

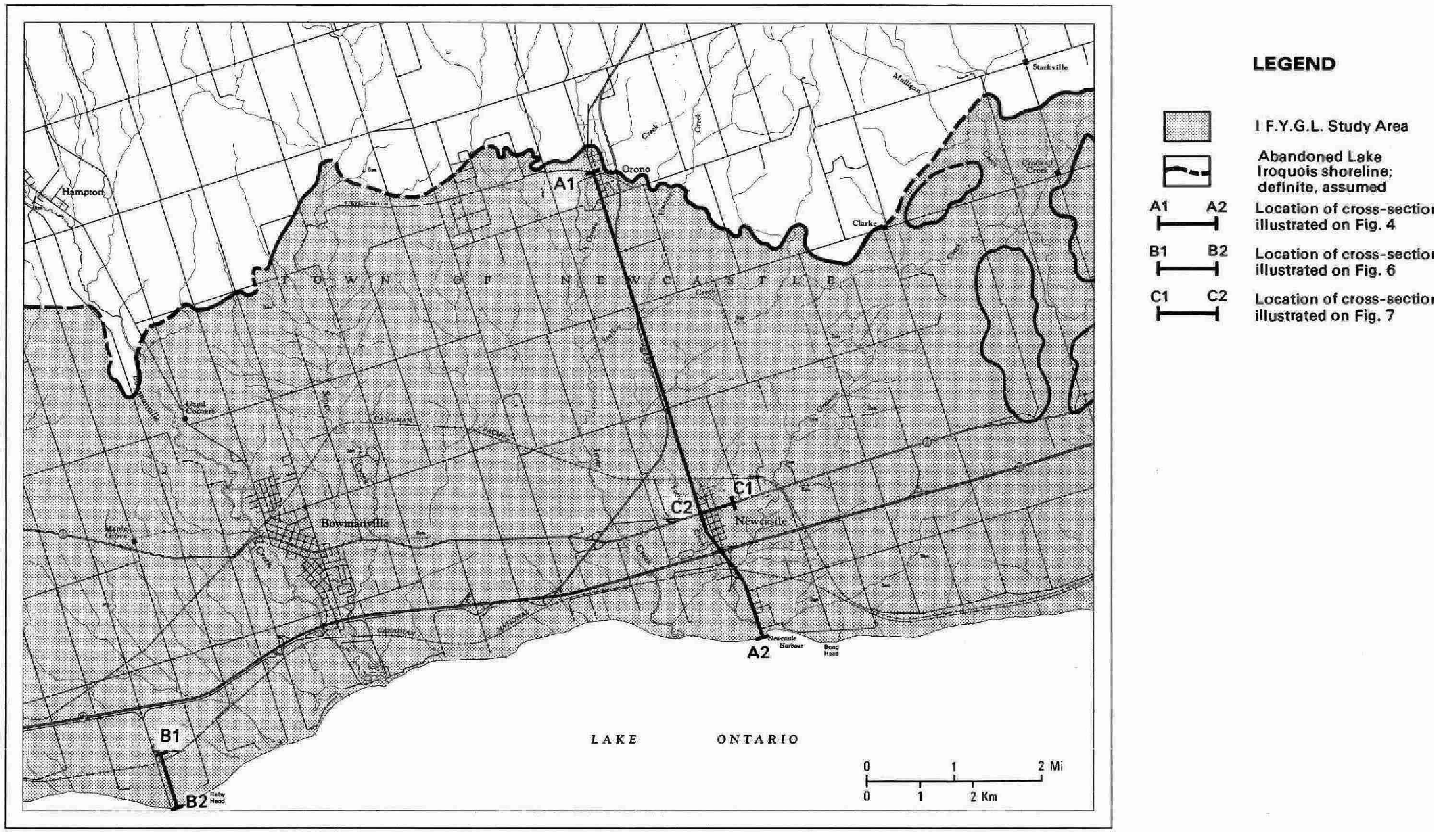

Figure 1b. The IFYGL study area containing the lower parts of the Bowmanville, Soper and Wilmot creeks drainage basin.

separation of the individual sand particles reduces the effective stress to such a low value that the sand liquifies. The sand will flow causing the collapse of the material above.

Springs, originating within permeable beds in the bluffs, have created ravines by continuously eroding headward. Some of these ravines have developed into steep-walled, amphitheatre-like openings behind the bluffs, with narrow ridges between the amphitheatres and the shore of Lake Ontario (Plates 1-6).

Drainage

Bowmanville Creek is the largest stream in the study area and enters the lake approximately one mile south of the Town of Bowmanville. Soper Creek is the largest tributary to Bowmanville Creek and joins it at the southern end of the Town of Bowmanville. Two other major streams, Wilmot and Graham creeks, flow into Lake Ontario to the southwest and southeast of the Village of Newcastle, respectively. Numerous minor streams with watersheds ranging from a few acres to two or three square miles, discharge directly into the lake at different points within the study area. All streams have cut deep, youthful valleys through the bluffs at their entrance to Lake Ontario.

Climate

According to the classification of climatic regions in Ontario by the Ontario Department of Agriculture and Food (1966), the study area lies within the "Lake Ontario Shore" climatic region.

The meteorologic data from the Orono station, located in the Police Village of Orono are given in Table 1 as an approximation of the climate within the study area. The 30 year (1941-1970) normal precipitation at this station is 34.20 inches. The long-term average annual temperature is 44.5°F, with a maximum temperature of 103°F recorded on July 10, 1936 and a lowest temperature of −30°F recorded on February 8, 1934.

Table 1. Meteorologic Data for Orono Station, Ontario. Normal, Maximum and Minimum Temperature and Precipitation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mean daily temperature (°F)	19.6	21.1	29.7	42.8	53.0	63.4	68.0	66.8	59.2	48.8	37.2	24.8	44.5
Mean daily maximum temperature	27.9	29.6	38.0	52.5	63.8	74.5	79.2	77.8	69.7	58.7	44.5	32.2	54.0
Mean daily minimum temperature	11.2	12.4	31.3	33.1	42.2	52.3	56.8	55.8	48.7	38.9	29.8	17.3	35.0
Extreme maximum temperature	55	59	72	84	90	95	103	97	94	81	73	61	103
Extreme minimum temperature	−26	−30	−19	1	21	32	37	32	23	9	−6	−26	−30
Mean rainfall (inches)	1.03	1.09	1.65	2.51	3.14	2.57	3.24	2.65	2.62	2.83	2.64	1.76	27.73
Mean snowfall (inches)	17.5	16.3	10.2	2.8	0.1	0.0	0.0	0.0	0.0	0.4	4.5	12.7	64.5
Mean total precipitation	2.77	2.72	2.67	2.80	3.14	2.57	3.24	2.65	2.62	2.88	3.09	3.05	34.20
Greatest rainfall in 24 hours	1.97	1.74	2.16	1.91	2.84	2.38	2.50	2.65	2.45	2.59	2.04	1.75	2.84
Greatest snowfall in 24 hours	11.0	10.7	10.2	6.5	2.4	0.0	0.0	0.0	T	4.5	16.5	14.0	16.5
Greatest precipitation in 24 hours	1.97	1.74	2.16	1.91	2.84	2.38	2.50	2.65	2.45	2.59	2.04	1.75	2.84

T—trace

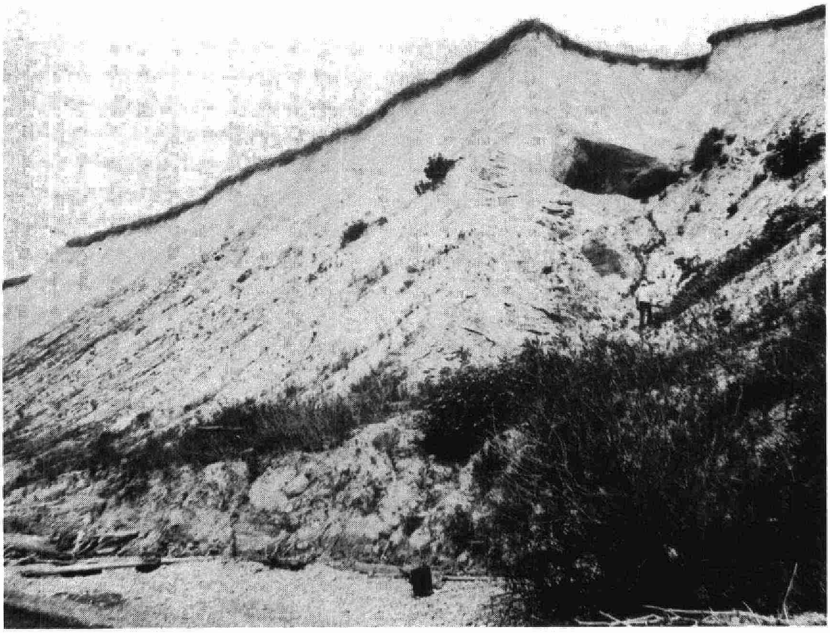

Plate 1. A small cave, created by ground-water discharge, in the upper right-hand portion of the picture marks the contact between glacial till over sand near the top of the bluff.

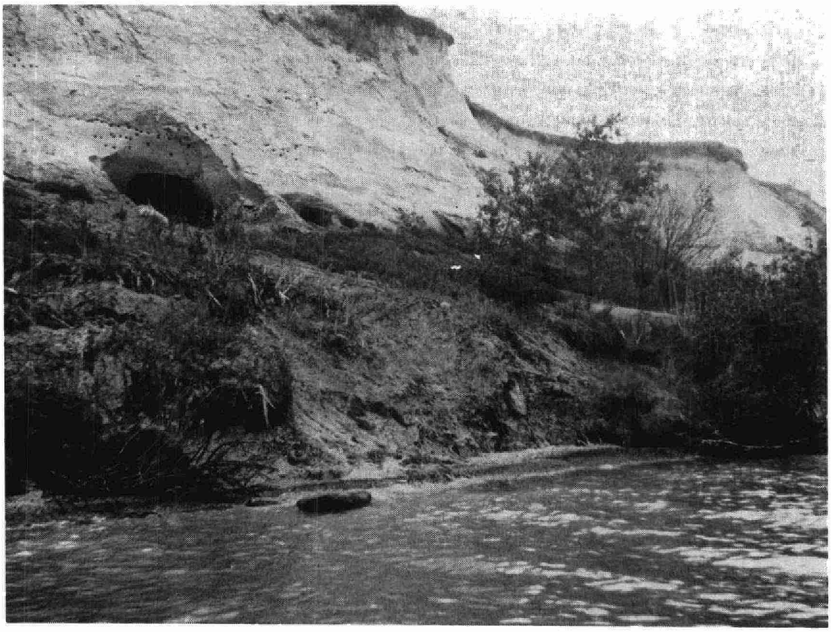

Plate 2. The upper limit of the vegetated slope roughly approximates the contact between sand and glacial till. Springs issuing at the base of the sand are marked by small caves. The upper limit of bird holes approximates the contact between the sand and overlying glacial till.

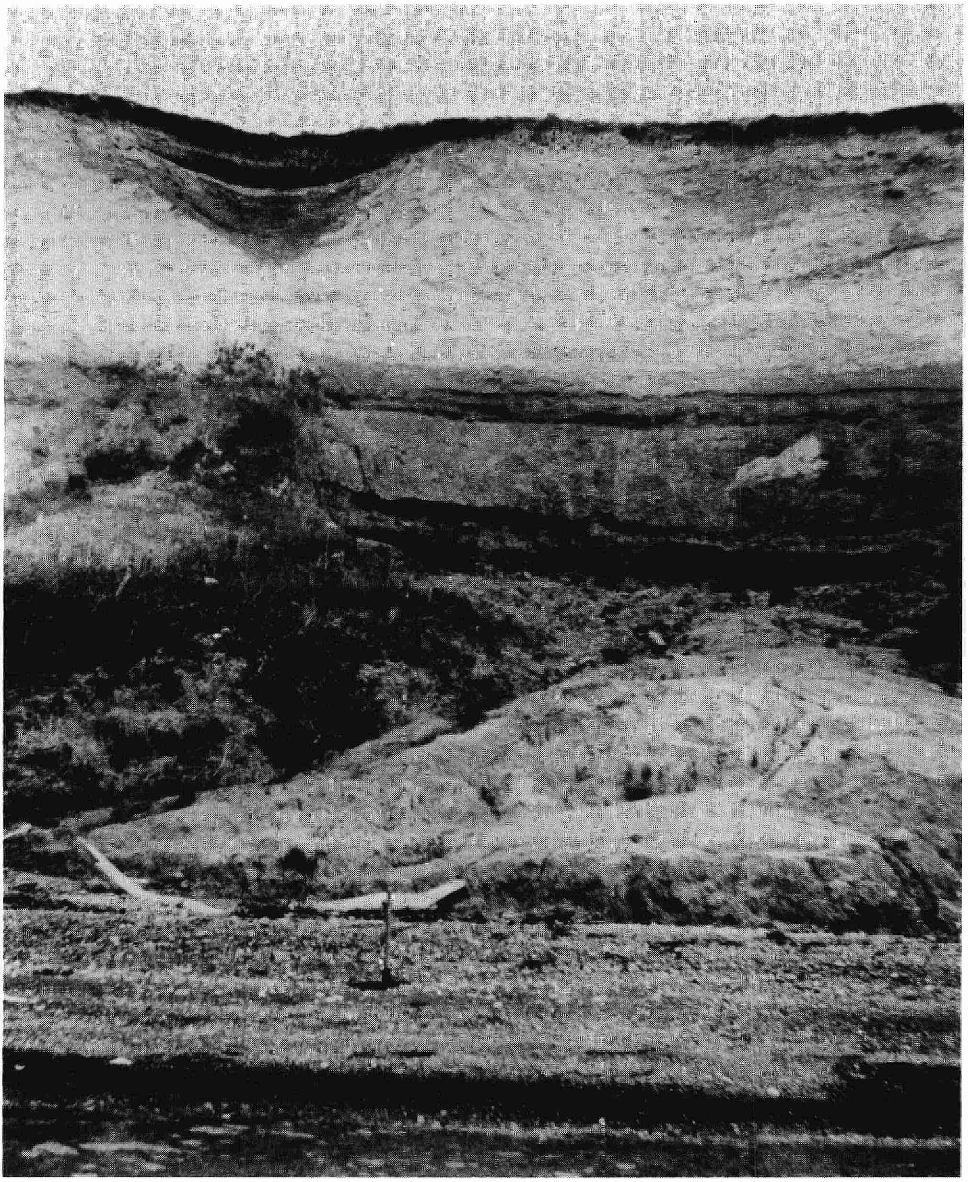

Plate 3. In the foreground, a mudflow of liquified sand and silt has been created by springs issuing at the contact between sand and glacial till. Note the relatively dry appearance of the glacial till overlying the wet (dark) permeable beds. At the top of the bluff in the upper left-hand part of the picture, an ancient channel with sand and gravel fill is exposed.

Plate 4. Landward erosion of the bluffs is indicated by the lower vegetated terrace of a large slump block created by ground-water erosion of the underlying material.

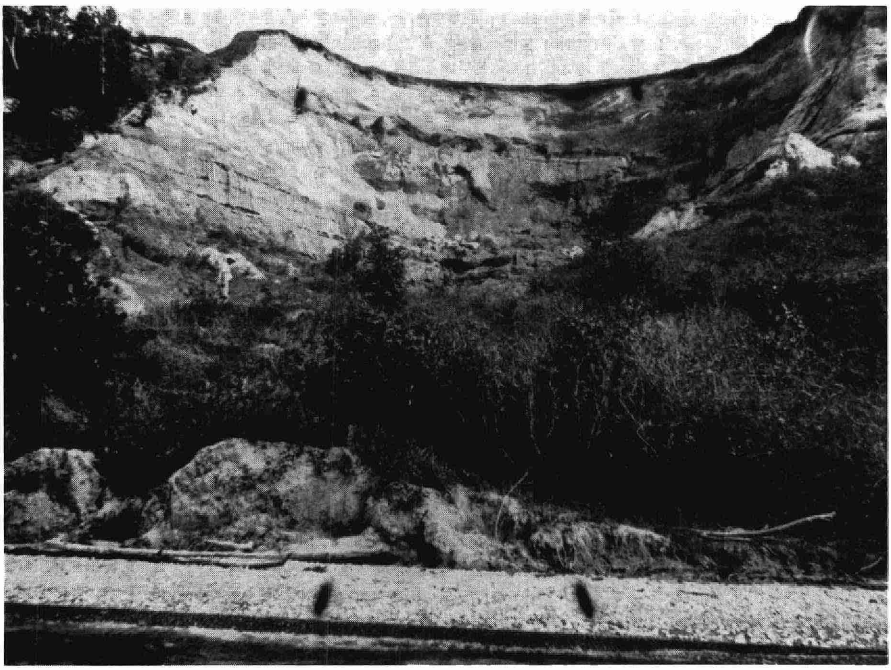

Plate 5. An early stage of an amphitheatre-like opening being developed in the bluffs.

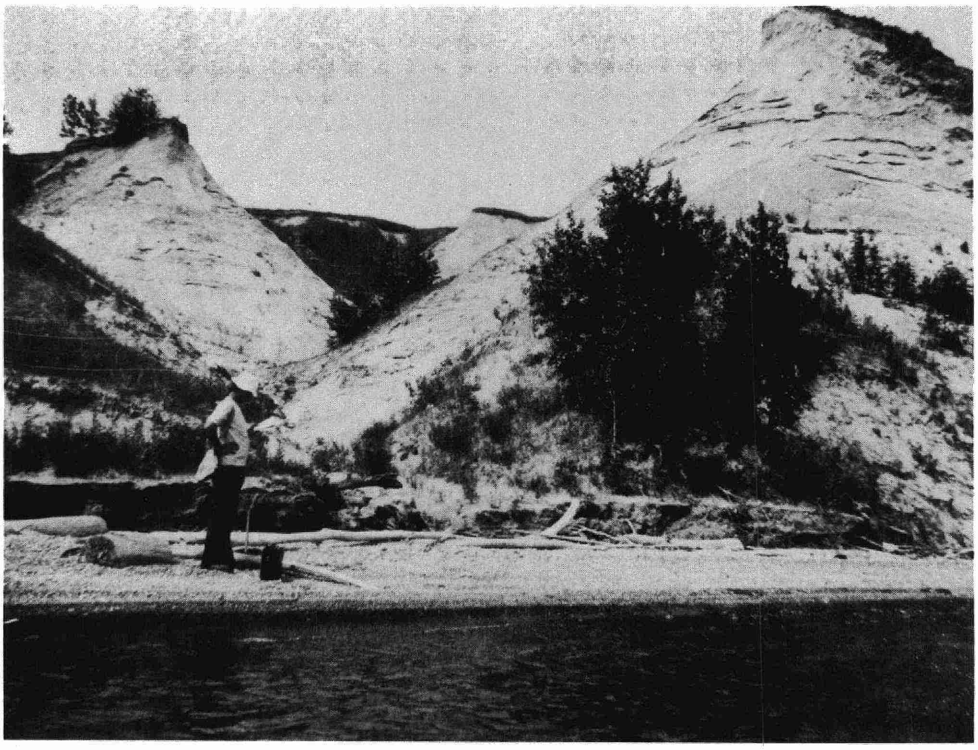

Plate 6. A sand ridge capped by glacial till and cut by a ravine separates an amphitheatre-like opening in the background from the shore.

GEOLOGY

Bedrock Topography and Geology

The bedrock in the study area is obscured by overlying deposits of glacial drift. The bedrock topography (Map 1) and the thickness of the overburden (Map 2) were compiled from water-well records that are available for the study area (Map 3). The depth to the bedrock at any location on Map 1 can be estimated by subtracting the bedrock-surface elevation from the land-surface elevation at that point.

The topography of the bedrock is similar to the present day topography. The highest elevations of the bedrock are found in the northern part of the study area and range from 330 to 370 feet above msl. The surface of the bedrock along the shore of Lake Ontario ranges from 194 to 234 feet above msl, which is approximately 10 to 50 feet below lake level. A bedrock high exists to the south of the Town of Bowmanville, extending to the Raby Head area, with its long axis parallel to the Lake Ontario shoreline. Its crest ranges from 311 to 331 feet above msl.

Bedrock valleys on Map 1 are indicative of pre-glacial drainage which is similar to the general southward flow of the present-day drainage. A significant difference occurs in the western part of the study area, where pre-glacial streams flowing southward had to swing abruptly westward due to the presence of the bedrock high (Map 1).

St. Mary's Cement quarry which is situated approximately one-half mile north of Lake Ontario, to the southwest of Bowmanville, reveals an excellent section of the bedrock (Plate No. 7) which is Ordovician in age (Liberty, 1969). The overburden in the quarry extends to a depth of about 30 feet and is underlain by dark, brownish-black shales (0-20 feet thick), of the middle and lower members of the Whitby Formation from the Nottawasaga Group. The areal extent of the shales appears to be limited to the western part of the study area, as their presence is not reported in water-well records east of Wilmot Creek. Dark, bituminous limestones of the Lindsay Formation from the Simcoe Group subcrop throughout the rest of the area.

According to Liberty (1969), the Whitby Formation is Upper Ordovician in age, whereas the Lindsay Formation is Middle Ordovician in age. The bedrock stratigraphy is shown in Table 2.

Surficial Geology

A detailed examination of the surficial geology at the southern edge of the study area was undertaken along 15 miles of the Lake Ontario shore from longitude 78°29′W to 78°46′W (Figure 2). The objectives of this study were to determine the origin, type and areal distribution of deposits within the overburden to arrive at a better understanding of the subsurface geology and to assess the amount of ground-water discharge from the overburden to Lake Ontario.

Plate 7. A section of the bedrock as seen in St. Mary's Cement Quarry to the southwest of Bowmanville. The overburden (the upper portion of the picture) is underlain by the shales of the Whitby Formation (above the contact line shown), which in turn are underlain by the limestones of the Lindsay Formation. Note the point discharges of ground water from the bedrock.

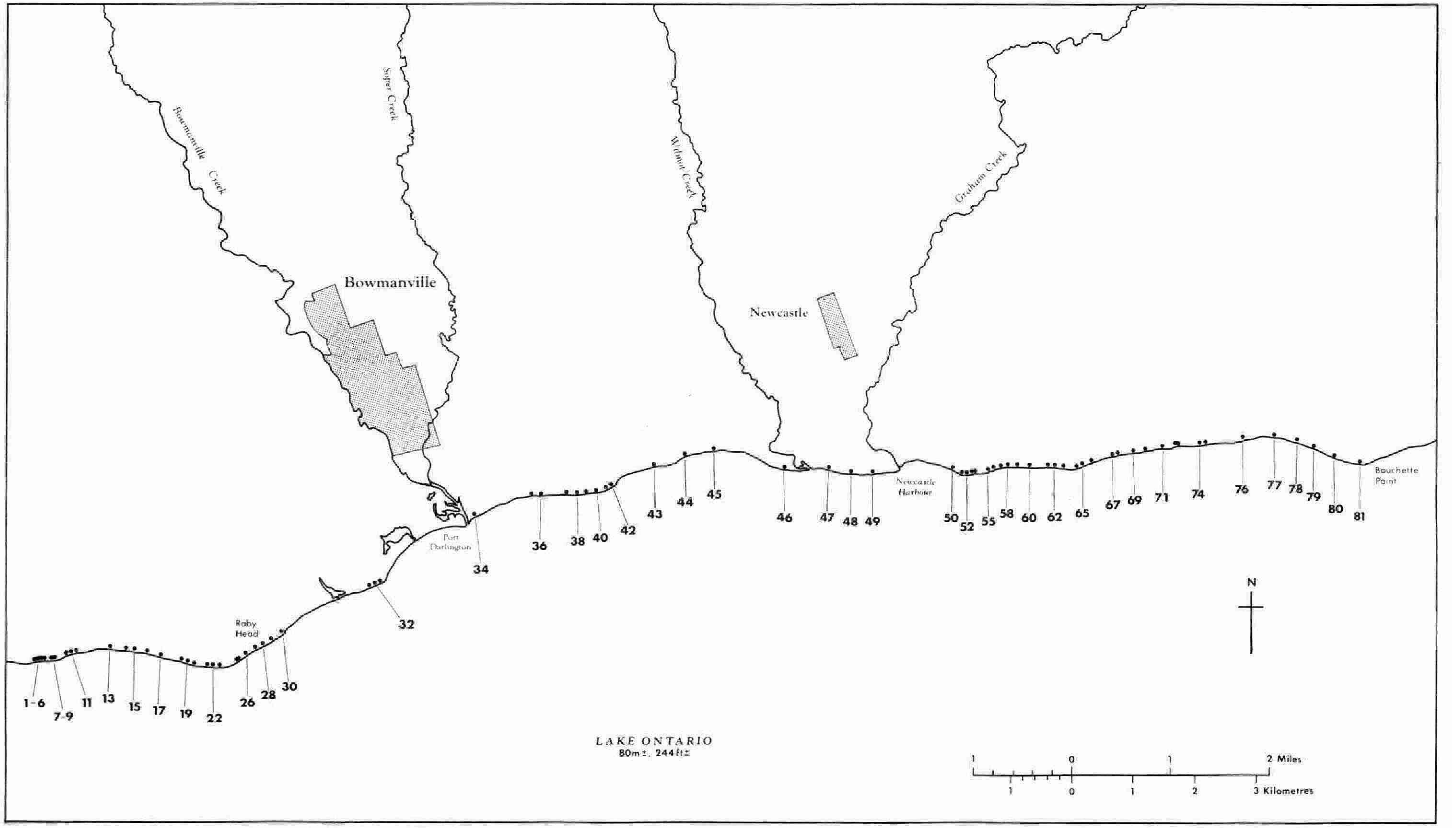

Figure 2. Locations of measured sections along the north shore of Lake Ontario in the Bowmanville-Newcastle area.

Plate 8. Stratified cross-bedded sands in a bar as seen in a gravel pit in the Iroquois Beach at Stephens Gulch.

Table 2. Stratigraphic Column of the Bedrock in the Bowmanville-Newcastle Area Based on Stratigraphic Nomenclature by Liberty (1969)

Era	Period	Epoch	Group	Formation	Member
Paleozoic	Ordovician	Upper	Nottawasaga	Whitby	Middle Lower
		Middle	Simcoe	Lindsay	
				Verulam	Upper Lower
				Bobcaygeon	Upper Middle Lower
				Gull River	Upper Middle Lower
			Basal	Shadow Lake	
Precambrian					

The surficial deposits within the study area, their type and areal distribution are illustrated on a portion of the geologic map published by Gravenor in 1957 (Map 2). As was indicated earlier, the study area is a part of the Iroquois Plain which is made up of ground moraine that was modified by the action of glacial Lake Iroquois. The nearshore deposits of Lake Iroquois consist of gravel and sand that are in the form of bars (Plate 8) and beach terraces. Most of the bars are several hundred feet south of the abandoned shoreline. Parts of the Iroquois Plain comprise varved silts and clays up to 30 feet in thickness. Till is exposed in both the eastern and western parts of the study area and in places has an elevation the same as or lower than the lake clays. Gravenor (1957) believes that the low-lying, till-surfaced areas represent those locations where strong currents prevented the deposition of clays and silts.

The stratigraphic succession as exposed in the bluffs along the examined shoreline (figures 3a, b, c, d) indicates that five major units are present. These units are:

1. a Proglacial Lake Unit consisting mainly of varved clay;
2. an Upper Glacial Unit made up of two till sheets separated by glacio-fluvial sands and silts;
3. a Middle Glacial Unit composed of till;
4. The Clarke Deposits Unit, consisting of a lower part of glacio-lacustrine clays and an upper part of glacio-fluvial sands;
5. a Lower Glacial Unit composed of till.

In addition, minor amounts of alluvial swamp and beach deposits of Recent Age overlie the above-mentioned deposits.

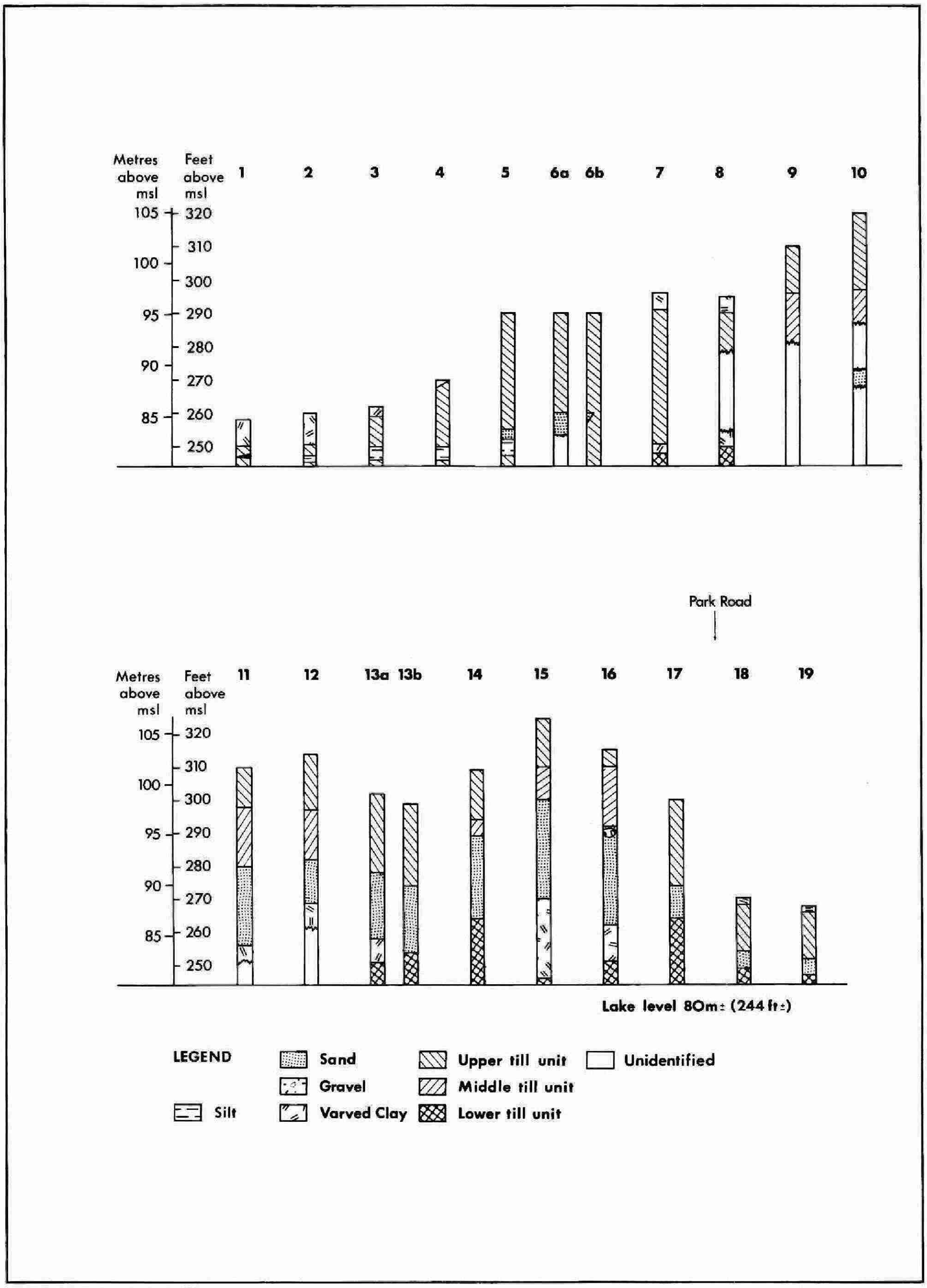

Figure 3a. Measured sections along the north shore of Lake Ontario in the Bowmanville-Newcastle area.

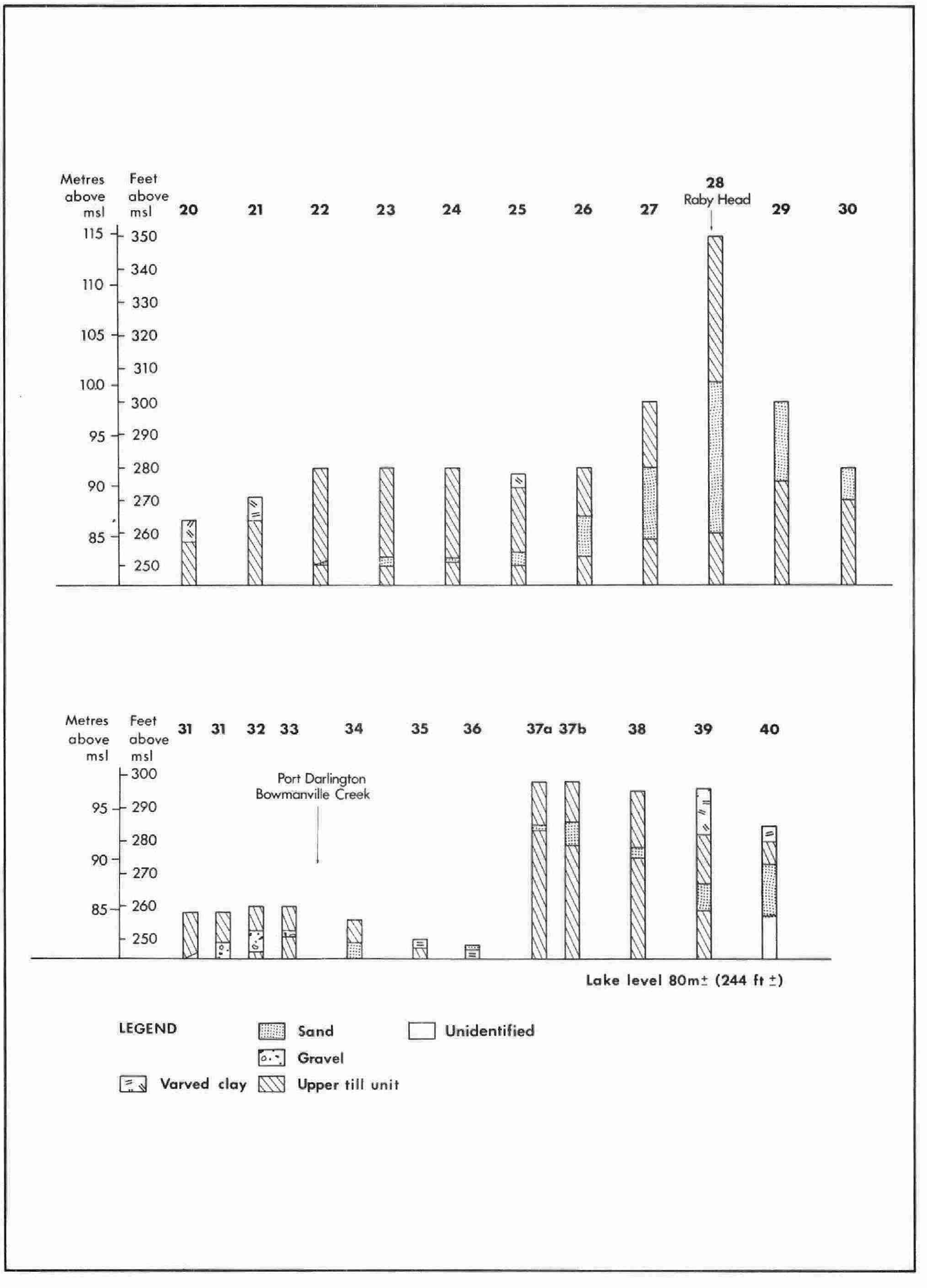

Figure 3b. Measured sections along the north shore of Lake Ontario in the Bowmanville-Newcastle area.

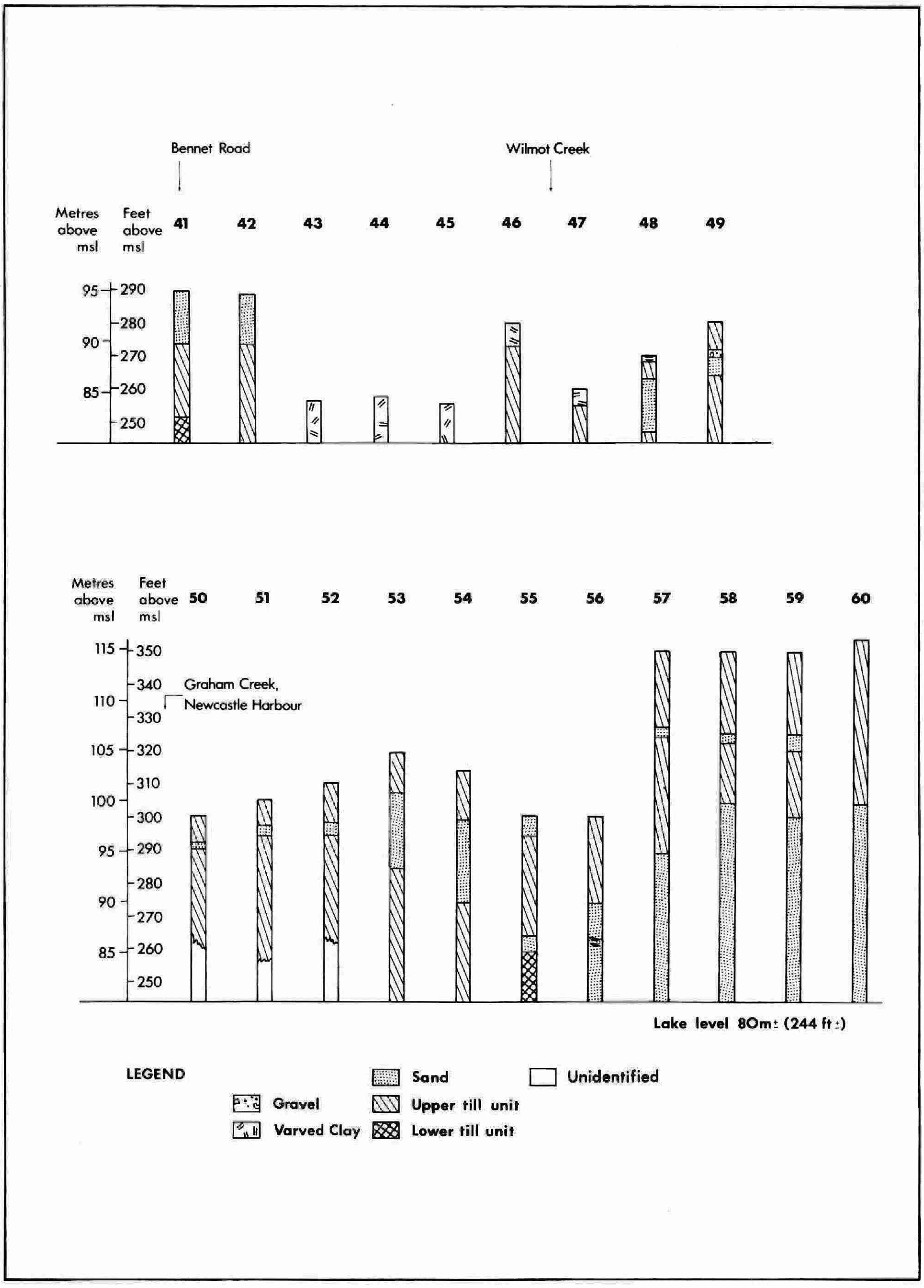

Figure 3c. Measured sections along the north shore of Lake Ontario in the Bowmanville-Newcastle area.

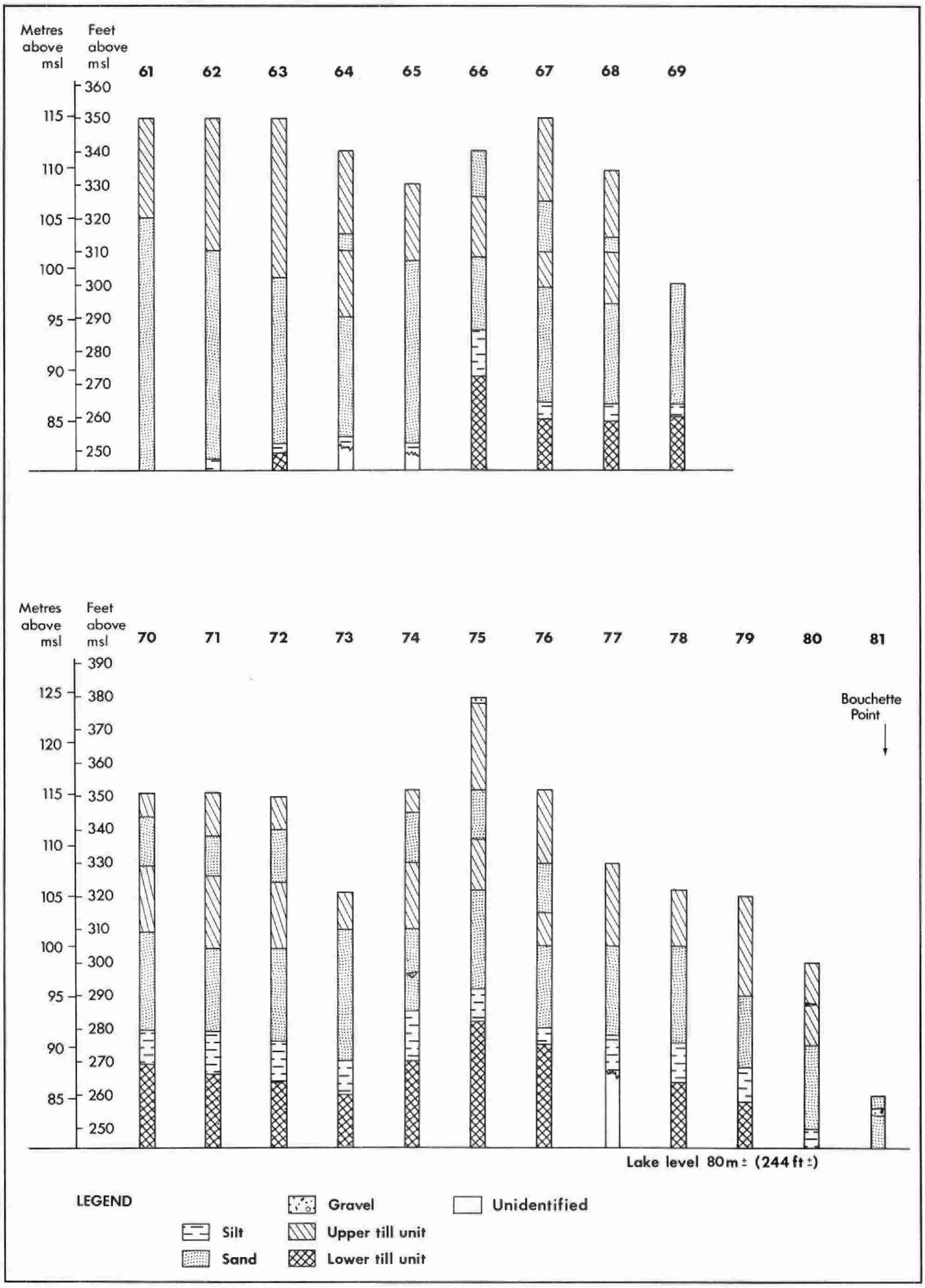

Figure 3d. Measured sections along the north shore of Lake Ontario in the Bowmanville-Newcastle area.

The Lower Glacial Unit

The Lower Glacial Unit consists of till and is exposed in the bluffs at the western, central and eastern parts of the examined shoreline. In the intervening areas, this till does not outcrop, but may be present below lake level. Data from records of water wells located near the shoreline indicate that this till rests on top of the bedrock. The thickness ranges from a few feet to a maximum of 36 feet (Section 75).

In general, this is a compact, dense silt to clay-silt till with a very low pebble content. Analyses of 9 samples from this till indicate an average of 31.6 percent clay, 51.6 percent silt and 16.8 percent sand. The till matrix averages 21.0 percent calcite and 7.1 percent dolomite, with a calcite to dolomite ratio of 2.9. Samples of this till collected from the eastern part of the shoreline show a higher calcite content, reflecting the presence of the Lindsay Formation at the bedrock surface in this area. Pebble counts indicate that 90 percent of the pebbles are limestone and shale with the rest being of Precambrian origin. Details of the till analyses are given in Table 3.

The lower till in the examined shoreline is comparable with the Sunnybrook Till, described by Karrow (1967) in the Scarborough area, which was assigned an early Wisconsinan age.

The Clarke Deposits Unit

A variety of stratified clay, silt and sand deposits that have a complex areal distribution overlie the lower till. Coleman (1909) names them "the deposits of the Clarke Interglacial Period," correlating them with similar deposits in the Toronto section. These deposits can be divided into two parts: a lower part consisting of varved clay or thin-bedded clay-silt and an upper part made up of sand.

The varved clay deposits are identified mainly in the western part of the bluffs. On a fresh surface, they consist of alternating thin beds, ¼ to 1 inch in thickness, of dark brown clay and light brown to light grey silt with fragments of light-coloured silt. The thickness of the varved clay deposits reaches a maximum of 24 feet in Section 15. Analyses of 3 samples yield average values of 35.0 percent clay, 58.0 percent silt, and 7.0 percent sand. Carbonate analyses from these samples averaged 32.0 percent calcite and 8.2 percent dolomite, with a calcite to dolomite ratio of 3.9.

The lower part of the Clarke Deposits in the eastern end of the study area consists mainly of well-sorted, evenly-bedded, grey-coloured clay-silt beds having a maximum thickness of 15 feet (Section 74). Analyses of 5 samples average 35.5 percent clay, 46.0 percent silt and 18.5 percent sand. The matrix material contains 49.6 percent calcite and 5.5 percent dolomite, with a calcite to dolomite ratio of 9.7.

The upper part of the Clarke Deposits consists of well-sorted, yellow-brownish, very fine to fine sand. The maximum thickness of this sand in the western part of the shoreline reaches 30 feet (Section 15), while it attains a thickness of over 75 feet in the eastern part (Section 61). Gravel lenses of limited extent are found within this sand (Sections 16, 56 and 74).

The Clarke sands constitute the main water-bearing horizon in the examined shoreline. Ground water discharges at the base of the sand in the form of springs. This hydrogeological property facilitated the mapping of the contact between the sand and the less permeable varved clay or clay-silt beds. Measurements of the discharges from 10 springs originating from the sand beds, along a 1700-foot section of shoreline to the east of the Village of Newcastle, on May 16, 1972, gave a value of 20 IGPM.

The lithological composition of the Clarke sediments suggests that the lower part of the varved clay and clay-silt is lacustrine and was deposited in a proglacial lake. The upper sand part is indicative of shallow-water or deltaic conditions in a high-level lake. The cross-bedding in the sand suggests southward flowing streams.

The general similarity between the Clarke Deposits and the Thorncliffe Formation described by Karrow (1967) in the Scarborough area, suggests a possible correlation. The Clarke Deposits can be regarded as mid-Wisconsinan interstadial deposits.

The Middle Glacial Unit

This unit is made up of till. Exposures of this middle till have only been identified in the western end of the examined shoreline (Sections 9, 10, 11, 12, 14, 15, and 16). The thickness of the till ranges from 5 to 12 feet in this locality. On a fresh surface, the till is a dark-brown, compact clay-silt till with a low pebble content. In texture, it resembles the lower till. Analyses of 4 samples yield an average of 32.4 percent clay, 53.9 percent silt and 13.7 percent sand. Carbonate analyses of the till matrix (4 samples) average 34.0 percent calcite and 6.5 percent dolomite, with a calcite to dolomite ratio of 5.5.

The stratigraphic position of this till on top of the Clarke Deposits and its lithologic character suggest that this deposit is a result of an ice advance correlative with that of the mid-Wisconsinan Meadowcliffe Till in the Scarborough area.

The Upper Glacial Unit

This unit is the youngest glacial deposit exposed in the bluffs and forms the surface material in most measured sections. The unit consists of two, lithologically similar tills separated by sand-silt deposits up to 45 feet in thickness (Section 28). In places the stratified deposits are missing and the two tills merge into one undifferentiated complex.

The lower till of this unit is grey in colour and it varies in thickness from a few feet to over 30 feet (Sections 37 and 53). Analyses on 14 samples of this till average 12.6 percent clay, 38.4 percent silt and 49.0 percent sand. Carbonate analyses on 15 samples average 36.5 percent calcite and 7.0 percent dolomite, with a calcite to dolomite ratio of 5.2.

The upper till of this unit is oxidized and buff in colour and its thickness ranges from 6 to 44 feet. Analyses on 18 samples of this till yield an average of 12.3 percent clay, 37.0 percent silt and 50.7 percent sand. Carbonate analyses (18 samples) on the till matrix average 39.3 percent calcite and 6.1 percent dolomite, with a calcite to dolomite ratio of 6.5.

The results of the mechanical and carbonate analyses and the discontinuity of the stratified deposits separating the two tills of this unit indicate that both till sheets are closely related. They represent two ice advances from the same ice lobe. The Upper Glacial Unit exposed in the bluffs is correlative with the Leaside Till which has been described by Karrow (1967) in the Scarborough area.

The stratified sediments separating the two tills of this upper unit consist mainly of silt and very fine, compact sand. These deposits represent the second water-bearing zone within the overburden in the examined shoreline. Due to their compactness and fine-grained composition, the sands constitute a poor aquifer. Ground-water discharge from these deposits is usually seen in the form of seepage faces.

The Proglacial Lake Unit

At different locations in the bluffs, where the relief is below 300 feet above msl, the Upper Glacial Unit is overlain by varved clay deposits. These sediments were deposited either in early peripheral lakes or in Lake Iroquois, preceding present Lake Ontario.

Lake Ontario Deposits

Along most of the shoreline in the study area, there is a beach of gravel and sand between the base of the bluffs and the lake. These sediments are the product of the erosion of the bluffs and their thickness varies from a few inches to a few feet.

In five localities, sand bars have been built across the intervening bays. The most important bays enclosed by these barriers are the harbours of Port Darlington and Newcastle.

Table 3. Analyses of Till Samples

Sample Number	Mechanical Analysis			Carbonate Analysis			Material
	Sand*	Silt*	Clay*	Calcite*	Dolomite*	Calc/Dol.	
8	21.0	44.0	35.0	9.0	4.0	2.5	Lower Glacial Unit
17	19.0	58.0	23.0	7.0	8.0	0.9	Lower Glacial Unit
19	21.5	44.0	34.5	22.2	9.4	2.4	Lower Glacial Unit
73	20.0	42.0	38.0	8.2	3.8	2.2	Lower Glacial Unit
83	13.0	54.5	32.5	26.0	6.8	3.9	Lower Glacial Unit
94	6.0	60.0	34.0	35.4	8.8	4.0	Lower Glacial Unit
95	15.0	49.0	36.0	—	—	—	Lower Glacial Unit
96	12.0	65.0	23.0	27.0	9.2	2.9	Lower Glacial Unit
97	24.0	48.0	28.0	34.0	7.8	4.4	Lower Glacial Unit
12	13.3	47.7	39.0	34.0	4.0	8.5	Middle Glacial Unit
13	11.7	41.9	46.4	39.0	7.0	5.5	Middle Glacial Unit
14	13.0	69.0	18.0	28.0	6.8	4.1	Middle Glacial Unit
21	17.0	57.0	26.0	34.2	8.4	4.1	Middle Glacial Unit
2	46.0	41.5	12.5	38.0	4.0	9.5	Upper Glacial Unit
3	42.0	40.0	18.0	41.0	5.0	8.2	Upper Glacial Unit
4	49.6	36.7	13.7	49.0	5.0	9.8	Upper Glacial Unit
5	41.7	35.1	23.2	42.0	5.0	8.4	Upper Glacial Unit
9	60.3	32.6	7.1	40.0	6.0	6.7	Upper Glacial Unit
11	49.0	45.4	5.6	35.0	7.0	5.0	Upper Glacial Unit
25	45.0	40.7	14.2	34.8	6.8	5.1	Upper Glacial Unit
26	45.0	42.7	12.3	38.8	7.0	5.5	Upper Glacial Unit

29	54.8	33.2	12.0	36.8	6.8	5.4	Upper Glacial Unit
31	50.0	38.0	12.0	40.4	6.8	5.9	Upper Glacial Unit
35	55.0	34.0	10.5	36.0	7.2	5.0	Upper Glacial Unit
37	42.0	41.0	17.0	49.6	6.4	7.8	Upper Glacial Unit
39	59.0	29.0	12.0	38.6	6.8	5.7	Upper Glacial Unit
52	53.0	42.2	4.8	37.0	6.8	5.4	Upper Glacial Unit
33	60.0	30.0	10.0	37.6	7.2	5.2	Upper Glacial Unit
36	44.0	36.0	20.0	41.2	6.0	6.9	Upper Glacial Unit
42	45.0	39.0	16.0	38.6	6.8	5.7	Upper Glacial Unit
43	43.0	49.0	8.0	34.0	8.2	4.1	Upper Glacial Unit
44	43.0	39.5	17.5	38.6	7.0	5.5	Upper Glacial Unit
45	49.0	37.5	13.5	37.3	7.7	4.8	Upper Glacial Unit
46	49.0	36.5	14.5	34.8	6.2	5.6	Upper Glacial Unit
50	47.5	44.5	8.0	35.2	6.0	5.9	Upper Glacial Unit
51	62.0	27.0	11.0	40.4	6.8	5.9	Upper Glacial Unit
57	46.5	40.5	13.0	37.8	7.0	5.4	Upper Glacial Unit
58	50.2	40.0	9.7	32.2	6.2	5.2	Upper Glacial Unit
60	52.7	31.5	15.7	34.4	7.6	4.5	Upper Glacial Unit
66	43.0	47.5	9.5	35.2	6.0	5.9	Upper Glacial Unit
76	55.0	32.0	13.0	36.0	7.4	4.9	Upper Glacial Unit
81	57.0	37.0	6.0	36.0	8.2	4.4	Upper Glacial Unit
82	—	—	—	35.4	8.8	4.0	Upper Glacial Unit
62	57.2	27.8	14.0	38.2	7.0	5.5	Upper Glacial Unit
64	53.0	41.0	6.0	39.0	5.2	7.5	Upper Glacial Unit
80	52.0	36.0	12.0	36.0	4.8	7.2	Upper Glacial Unit

*Percentage

Swamp and Bog Deposits

Swamp and bog deposits are found in the lagoons that are enclosed by the beach bars. They consist of marl, gytja and organic matter with a thickness of 2 to 3 feet.

Correlation with the Toronto Section

Coleman (1909) was first to correlate the Clarke Deposits with the Toronto section. Coleman regarded the Clarke Deposits as interglacial placing them between the Iowan and the Wisconsinan glacial stages.

Coleman's classification was modified by Keele (1924). In a report on the clay and shale deposits of Ontario, Keele suggested that the Clarke Deposits were laid down in a glacial lake between two advances of the same ice sheet. Thus, Keele reduced the Clarke Deposits from interglacial to interstadial rank, pushing up their age to Wisconsinan.

Coleman (1932) published a new classification of the Pleistocene deposits in the Toronto section which is as follows:

Upper till—Wisconsinan
Interglacial sand—Sangamon
Middle complex of tills—Illinoian
Toronto Formation, Scarborough Beds and Don beds—Yarmouth
Lower till—Kansan or Nebraskan

Though Coleman did not mention the Clarke Deposits in his new classification, it is clear that he pushed their age back into the Sangamon interglacial stage.

Dreimanis and Terasmae (1958) suggested a new classification for the Toronto section, based on mineralogical analyses of tills. They assigned all the tills above the Scarborough beds to Wisconsinan stages.

Karrow (1967) provided the latest classification for the Pleistocene deposits in the Scarborough area east of Toronto (Table 4). Karrow regarded the Don Formation as Sangamonian and assigned the sediments from the Scarborough Formation up to and including the Iroquois deposits as early, middle and late Wisconsinan substages.

The correlation chart as given in Table 4 is suggested for the Bowmanville-Newcastle area.

Table 4. Suggested Correlation Chart

Stage		Scarborough Section After Karrow (1967)	Bowmanville-Newcastle Section
Recent		Lake Ontario Deposits Swamp and Bog Deposits	Lake Ontario Deposits Swamp and Bog Deposits
Wisconsinan	Late	Lake Iroquois and early peripheral lakes	Proglacial Lake Unit
		Leaside Till	Upper Glacial Unit
		Lake and stream deposits	
		Meadowcliffe Till	Middle Glacial Unit
		Lake and stream deposits	
		Seminary Till	
	Middle	Thorncliffe Formation	Clarke Deposits Unit
	Early	Sunnybrook Till	Lower Glacial Unit
		Scarborough Formation	not present
Sangamonian		Don Formation	not present
Illinoian		York Till	not present

GROUND WATER

General Principles and Definitions

Subsurface waters occur in two zones below the land surface: the unsaturated zone and the saturated zone. The first zone extends from the land surface down to the water table and it includes the capillary fringe. This zone contains liquid water under less than atmospheric pressure, and water vapour and air or other gases at atmospheric pressure. In parts of this zone, interstices, particularly the small ones, may be temporarily or permanently filled with water. The second zone (i.e. the saturated zone) is that zone in which all voids, large and small, are filled with water under pressure greater than atmospheric (Lohman, 1972). The top boundary of the saturated zone at which pressure is atmospheric is called the water table. Ground water is that part of the subsurface waters which occurs in the zone of saturation and is subject to continuous movement. The geometry and intensity of ground-water flow are dependent on the hydrogeologic environment consisting of topography, climate and geology (Toth, 1972). The source of and recharge to the ground water comes from precipitation directly by infiltration from the land surface or indirectly by surface water leaking from streams, ditches or ponds. The land-surface topography exerts a controlling influence upon the configuration of the water table, the distribution of flow systems, and consequently ground-water movement. The occurrence, movement, quality and availability of ground water also depends on geologic factors, in particular, lithology, porosity, permeability and the areal distribution of the various deposits.

Ground water occurs in the openings within the aquifer. These openings may be in the form of pore spaces between grains of silt, sand or gravel, or in the form of solution cavities, fissures, joints and bedding planes. The ratio of the volume of the pore spaces to the total volume of the water-bearing material is called the porosity.

In unconsolidated deposits porosity is controlled by the shape, arrangement, degree of sorting and cementation of the grains. Porosity is high in well-sorted deposits and low in poorly sorted and highly cemented deposits. In consolidated rocks, porosity is dependent on the degree of development of the fissure system and solution-cavity openings. Effective porosity refers to the amount of interconnected pore space or other openings available for fluid transmission.

Ground-water flow occurs under a hydraulic gradient which is defined as the change in static head per unit of distance along the ground-water flow path. The relative ease with which a water-bearing material can transmit water under a hydraulic gradient is a measure of the permeability of the material.

Ground-Water Occurrence in the Bedrock

Within the study area, ground-water occurs in fissures, joints and bedding planes of the bedrock formations. The development of the fracture system within the bedrock is relatively limited because the region was tectonically stable throughout geologic time. The widening of the fractures existing within the bedrock, and consequently the formation of solution cavities

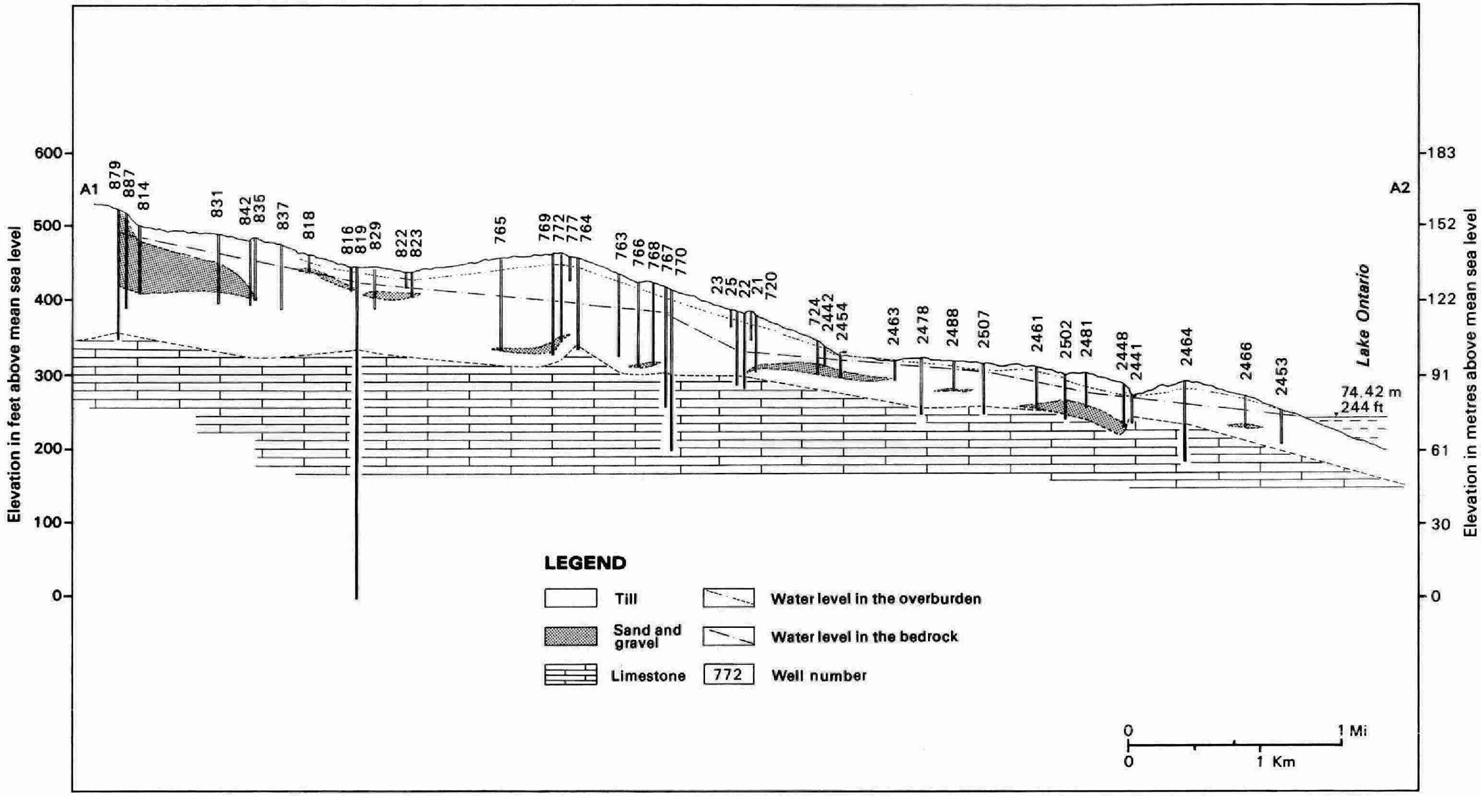

Figure 4. Cross-section A1-A2 extending from the Police Village of Orono to Bondhead on Lake Ontario. The location of this cross-section is shown on Figure 1b.

due to the dissolution of the calcium carbonate in the limestone by chemically aggressive ground water appears to be of minor importance in the study area. The absence of such solution cavities within the bedrock formations can be explained as follows:

(i) The presence of a glacial mantle with a relatively high carbonate content results in percolating ground water becoming saturated with respect to $HCO3^-$ and Ca^{++} ions before it reaches the bedrock.

(ii) The limestone rock unit is dense, compact and impure with a high clay content, tending to hinder its dissolution.

(iii) The number of fissures and joints is relatively limited and their distribution is irregular, both horizontally and vertically; therefore, the surface of the rock only is open to dissolution.

(iv) The hydraulic gradient is low, limiting the quantity of chemically aggressive water acting on the rock.

Over 85 wells in the study area are completed in the bedrock. Most of these wells penetrate only the upper few feet of the bedrock (1-50 feet). Four wells are reported to penetrate the bedrock from 70 to 80 feet, one well to 235 feet, and another well to 300 feet. These deep wells are either dry or have a very low yield. It would appear that ground-water supplies obtained from the bedrock come mainly from its upper part, where the availability of ground water is controlled by the distribution of the water-yielding openings and the type and thickness of the overburden deposits. In general, wells completed in the bedrock are suitable for supplying domestic requirements only. The production from these wells ranges from a few gallons per day to a few gallons per minute with some of the wells being pumped dry under normal usage.

Ground-Water Occurrence in the Overburden

The overburden in the study area is composed of glacial till, glacio-fluvial sands and gravels, glacio-lacustrine silts and clays and recent alluvium and organic matter. Ground water occurs within the overburden in the pore spaces between the grains of the unconsolidated materials. Clays, though highly porous, have such small pore spaces that a large percentage of the water contained in them is bound to the particles by forces of molecular adhesion. These sediments are usually described as being impermeable. In the study area, the composition of the overburden is highly variable, both vertically and laterally. Examination of the surficial geology along the shoreline of Lake Ontario, where the overburden section is well exposed, clearly illustrates this point.

Over 200 wells are completed in the overburden within the study area. Many well logs indicate the presence of sand or gravel deposits at depths which appear to be, in some instances, thinly isolated bodies (Figure 4). The available data indicate the presence of an aquifer whose areal distribution closely follows the bedrock lows to the east of the Town of Bowmanville and in the vicinity of the Village of Newcastle. This aquifer consists mainly of gravel, ranging in thickness from 1 to 40 feet. The areal distribution of the aquifer within the bedrock lows and its composition (mainly gravel) suggest that it is a buried channel deposit.

As was described earlier, sand and gravel bars and beach terraces are well displayed at surface along the abandoned Iroquois shoreline. The thickness of these deposits ranges from a few feet to 20 or 25 feet. At Gaud Corners on Bowmanville Creek, a deep valley has been cut since the time of Lake Iroquois and a still deeper and wider one on Soper Creek at Stephens Gulch, approximately 3 miles north of the Town of Bowmanville. The Iroquois deposits give rise to a number of springs which are located a little east of the Village of Tyrone, half way between the two valleys. These springs which discharge approximately 200 gallons per minute are used as part of the water supply for the Town of Bowmanville.

Logs of water wells located to the southwest of Gaud Corners on Bowmanville Creek, approximately 1 mile to the south of Stephens Gulch on Soper Creek and immediately to the south of Orono on Wilmot Creek, indicate the presence of sand beds that have a continuous thickness of over 100 feet. The origin of these sands is unclear. They may be deltaic deposits formed at the mouths of Bowmanville, Soper and Wilmot creeks as they entered Lake Iroquois or a lower-level postglacial lake. On the other hand, the uppermost few feet of these deposits could be associated with Lake Iroquois, while their lower part could be correlated either with the Clarke Deposits or with the fluvial deposits within the Upper Glacial Unit.

The sands and silts associated with the Clarke Deposits and with the Upper Glacial Unit constitute the major water-bearing deposits that outcrop in the bluffs along the present Lake Ontario shoreline. The location, thickness and areal distribution of these deposits within the bluffs have been described earlier in the section on surficial geology (Figure 3).

A panel diagram was constructed, based on the logs of 68 wells drilled in the Raby Head area (Figure 5). This diagram indicates that the thickness of the fluvial deposits varies from more than 60 feet at one point along the bluffs to pinch out inland. This discontinuity of the fluvial deposits, as illustrated in Figure 5, the lack of enough control data inland, and the complexity of the geologic conditions make it impossible to construct a geologic model that approximates the natural conditions closely.

The ground-water availability in the overburden ranges from poor to good. In general, only domestic supplies and limited livestock requirements are met. Locally, overburden aquifers are the most productive sources of ground water within the study area. The Tyrone springs are used as a water-supply source for the Town of Bowmanville. These springs satisfy approximately half the water requirements of the town, with the other half being obtained from Lake Ontario. The water supply for the Village of Newcastle is obtained from a gravel aquifer which is located in the vicinity of the village. Two municipal wells tap this aquifer and produce over 200 IGPM. The Police Village of Orono obtains its water supply from a municipal well drilled into an overburden aquifer.

Ground-Water Movement

Ground-water is subject to continuous movement, the rate of which is a function of the hydrogeologic characteristics of the material in which it moves, and the existing hydraulic gradients. The existence of a three-dimensional, continuous ground-water domain in a corresponding three-dimensional potential field has been established and developed by Hubbert (1940), Toth (1962, 1963), and Freeze and Witherspoon (1966, 1967).

The ground-water hydraulic potential at a given point in this domain is given by:

$$\Phi = gz + (P - Po)/\rho \tag{1}$$

where Φ = hydraulic potential at a given point in the field,
g = gravity acceleration,
z = elevation at the point above an assumed datum,
Po = atmospheric pressure,
P = pressure at given point,
ρ = density of water. (Hubbert, 1940)

The hydraulic head (ϕ) equals the hydraulic pontential (Φ) divided by the gravity acceleration (g) and is measured in feet above a datum (usually msl). Because the hydraulic head is obtained by dividing the hydraulic potential by a constant it is a potential quantity itself and obeys the laws of potential theory (Freeze, 1966). The hydraulic head, therefore can be used as a potential function to describe the ground-water flow system.

Within the framework of this approach to the ground-water regime, the water table is defined as the upper boundary of the ground-water flow system at which the absolute pressure is atmospheric. The ground-water domain contains areas of recharge, lateral transfer and discharge. Recharge areas are defined as those areas where water, from precipitation or surface bodies of water, enters the ground-water system at the water-table surface, and flows away from the water table within the saturated zone. Discharge areas are those where the flow of ground water is towards the water table within the saturated zone and water is removed from the ground-water system, usually to surface-water flow (Freeze, 1969).

Following the recent development of the ground-water flow theory, the ground-water regime in the study area will be considered to be a hydraulically continuous, three-dimensional domain, divided into several adjoining hydrologic units. The upper boundary of each unit is the water table, and the lower boundary is an assumed horizon within the bedrock, *including its upper 50 feet.* All formations above this boundary are considered to be permeable. Each hydrologic unit is bounded on all sides by imaginary impermeable boundaries representing the ground-water divides.

Within the study area, the hydrologic units of Bowmanville, Soper and Wilmot creeks are open to the north, whereas Foster Creek and numerous other small streams form closed hydrologic units.

Knowledge of the water-table configurations is of great importance in ground-water investigations as it indicates the direction and rate of ground-water movement. Water levels in a water well are a function of the well's location, depth and sub-surface geology. Maps of the water-table configuration should be based on measurements of water levels in shallow wells only. As the number of such wells are limited in the study area, a general water-level map was constructed based on water levels in all wells that were completed in the overburden (Map 4). Water levels in wells that were completed in the bedrock are also indicated on this map. This water-level map gives an indication of the general direction of the ground-water movement and illustrates the relative values of the hydraulic head in the bedrock and the overburden. The map also indicates the following:

(i) Topography exerts a controlling influence on ground-water movement and the topographic divides coincide closely with the ground-water divides.

(ii) Ground water flows from the ground-water divides towards valleys or into Lake Ontario.

(iii) Water levels in wells located near the ground-water divide and completed in the bedrock exhibit lower values in comparison with those wells completed in the overburden, the reverse picture being generally observed in bedrock wells located in the valleys.

(iv) Several local flow systems exist where flow occurs from local topographic highs to adjacent topographic lows.

(v) The gradient causing ground-water flow derived from the distance and difference in elevation between two contour lines average 0.02 feet per foot.

The Ground-Water Potential Field, Mathematical Basis and Boundary Conditions

In order to solve ground-water flow problems only two equations are available: the equation of motion and the equation of continuity. For the flow of ground water, the Darcy's formula assumes that the friction losses accompanying ground-water movement are directly proportional to the velocity. In an x, y, z co-ordinate system, Darcy's Law can be applied to the flow in any one of these directions so that we can write:

$$V_x = K\ (x, y, z)\ \partial\phi / \partial x \tag{2}$$

$$V_y = K\ (x, y, z)\ \partial\phi / \partial y \tag{3}$$

$$V_z = K\ (x, y, z)\ \partial\phi / \partial z \tag{4}$$

where V_x, V_y, V_z = the velocities in the x, y, z directions,
$K\ (x, y, z)$ = the coefficients of permeability in the x, y, z directions,
ϕ = the hydraulic head.

For a steady state flow of an incompressible fluid, the equation of continuity has the form:

$$\frac{\partial Vx}{\partial x} + \frac{\partial Vy}{\partial y} + \frac{\partial Vz}{\partial z} = 0 \tag{5}$$

The equation that governs steady state flow is a combination of Darcy's Law and continuity. Thus, by substituting equations 2, 3 and 4 in equation 5, we obtain Richard's equation:

$$\partial/\partial x\left[K(x,y,z)\frac{\partial\phi}{\partial x}\right] + \partial/\partial y\left[K(x,y,z)\frac{\partial\phi}{\partial y}\right] + \partial/\partial z\left[K(x,y,z)\frac{\partial\phi}{\partial z}\right] = 0 \tag{6}$$

(Freeze and Witherspoon, 1966)

For a saturated homogeneous medium, where K is constant, Richard's equation yields Laplace's equation:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{7}$$

which can be solved as a boundary value problem to give the potential distribution in a given saturated medium defined by a set of boundary conditions.

The observed distribution of ground-water *potential* within the overburden is shown in a cross-section (B1-B2) located in the Raby Head area (Figure 6). The figure is based on measurements made on September 29, 1971, in 8 piezometers and observation wells and illustrates the ground-water flow into Lake Ontario. A short distance from the lake, a local discharge zone occurs in the section. Here a flowing well exists which is due to the change in the lithology and thickness of the permeable sand-silt beds. In the figure, the ground-water divide location is not shown because of the lack of data.

The steady state *potential* distribution in a two-dimensional cross-section using linear triangular finite elements (Frind, 1972) was made. The selected cross-section (C1-C2) is situated to the east of the Village of Newcastle, within the study area, and is composed lithologically of three layers, bedrock, gravel and till (Figure 7). This cross-section extends for 2,500 feet from the water divide to Foster Creek, at right angles to the water-table contours which were approximated from the existing well data.

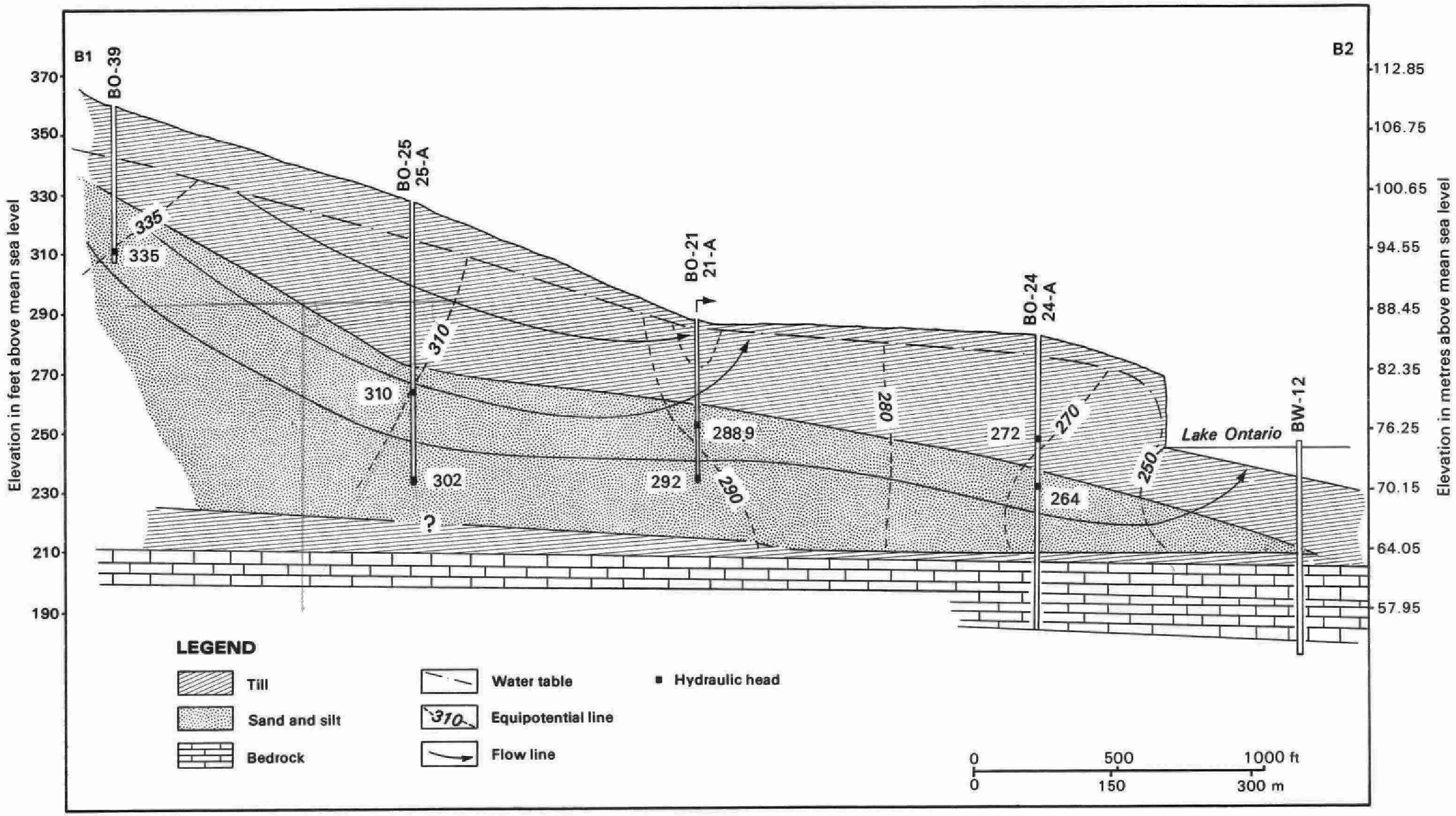

Figure 6. Observed potential distribution in cross-section B1-B2 in Raby Head area, based on measurements made on Sept. 29, 1971. The location of this cross-section is shown on Figure 1b.

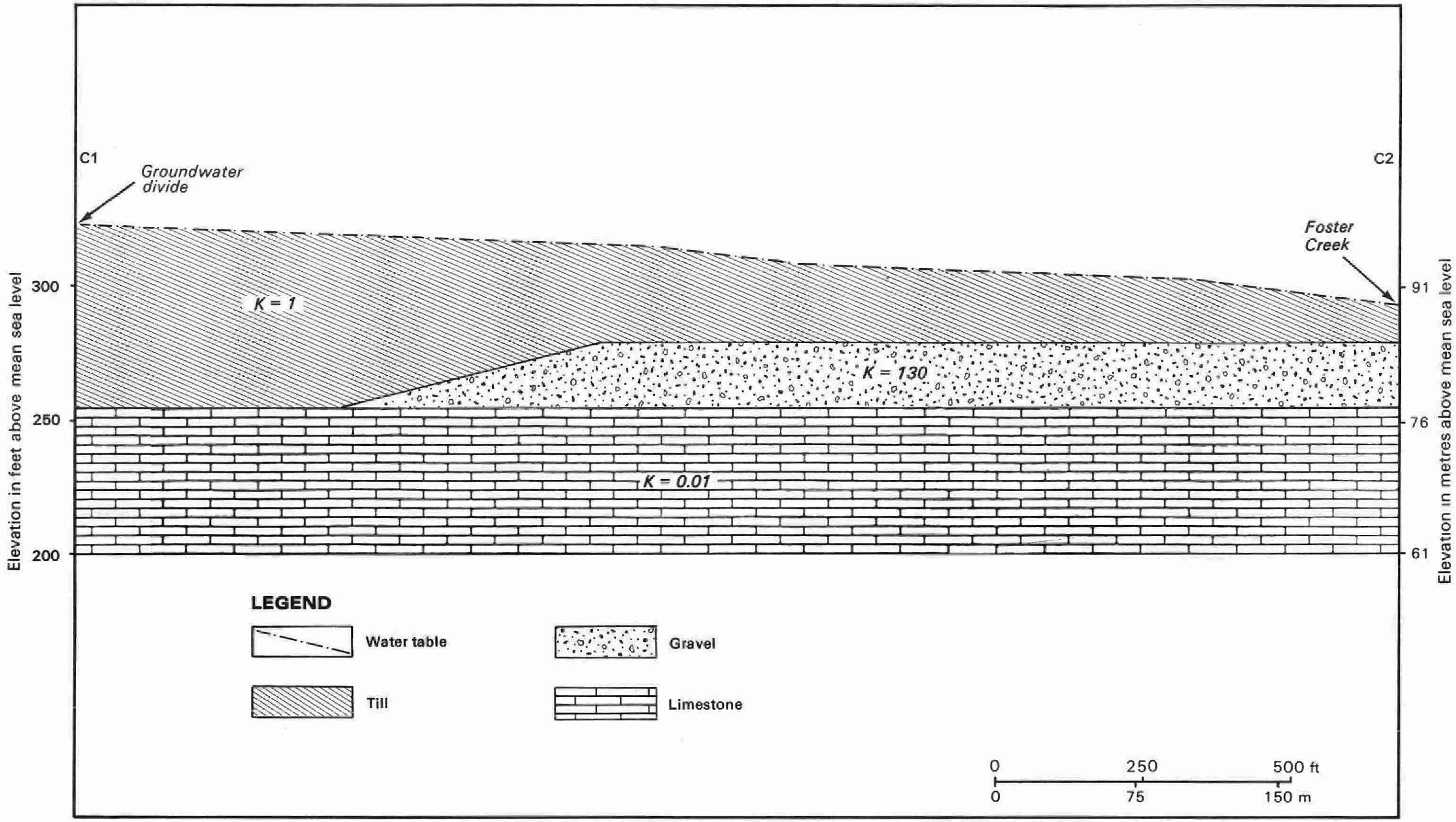

Figure 7. **Newcastle schematic geological cross-section C1-C2. The location of this section is shown on Figure 1b.**

The numerical solution is based on the following assumptions:

(a) Steady state flow conditions (i.e. configuration of the water table is constant and does not change with time).

(b) The water table represents the upper boundary of the potential field, so that: $\phi = Y(x)$ (Figure 8).

(c) The bedrock is completely impermeable at a depth of 55 feet below the bedrock surface and this depth horizon was considered to represent the lower boundary. As it is completely impermeable, then:

$$\frac{\partial \phi}{\partial y} = 0 \tag{8}$$

(d) The cross-section is bounded by two imaginary lines, at the ground-water divide and the stream, through which there is no flow, then:

$$\frac{\partial \phi}{\partial x} = 0 \tag{9}$$

It was found after several trials that the set of permeability values of 1, 130, 0.01 for the till, gravel and bedrock, respectively, are the best values that reproduce the actual observed *potential* through the cross-section (Figure 9).

Water-Level Fluctuations

Water levels in wells are almost constantly fluctuating and decline or rise within a relatively short time. Water-level fluctuations reflect the quantity of water stored in aquifers and the movement of ground water. A continual decline in water levels results when discharge exceeds recharge; water levels usually rise when recharge is greater than discharge.

Data for the water-year 1971-1972, from water-level recorders in a number of deep observation wells and periodic water-level measurements (once or twice a month) in 17 abandoned shallow wells were made available through the IHD program of the Ministry. Water-level fluctuations in some of these wells are illustrated in figures 10-14. All the hydrographs show a maximum water level during the period May 3 to May 15 which is followed by a continuous decline during June to November. In general, the water levels rise during the winter months December to February. The largest rise in water levels, however, occurs during April and the first half of May which coincides with the snow melt period where soil moisture is at field capacity.

Data on the minimum, maximum and range of water-level fluctuations during the water-year 1971-1972 are given in Table 5. The range of water-level fluctuations varies from 0.96 feet to 11.11 feet and averages 5.80 feet.

Table 5. Data on Water-Level Fluctuations in Observation Wells during the Water-Year 1971-1972

Well No.	Minimum Recorded Level (ft.) below Ground Surface	Maximum Recorded Level (ft.) below Ground Surface	Range of Fluctuations (ft.)
B-4-a	7.71	6.75	0.96
S-7	38.43	35.60	2.83
W-3	40.85	39.70	1.15
W-5A-a	10.95	1.95	9.00
W-5A-b	11.75	2.95	8.80
W-5B	11.25	2.75	8.50
WS-14	18.33	7.62	10.71
WS-17	14.57	6.67	7.90
WS-19	6.17	2.70	3.47
WS-20	13.90	2.88	11.02
WS-22	5.74	4.38	1.36
WS-23	11.06	6.44	4.62
WS-24	9.90	4.00	5.90
WS-25	15.71	4.60	11.11
WS-27	23.23	15.28	7.95
WS-30	4.04	2.62	1.42
WS-33	5.45	3.24	2.21
WS-35	23.56	19.73	3.83
WS-36	33.23	31.76	1.47
WS-38	12.59	5.83	6.76
WS-39	16.10	10.05	6.05
WS-41	25.93	16.36	9.57
WS-42	32.40	23.70	8.70

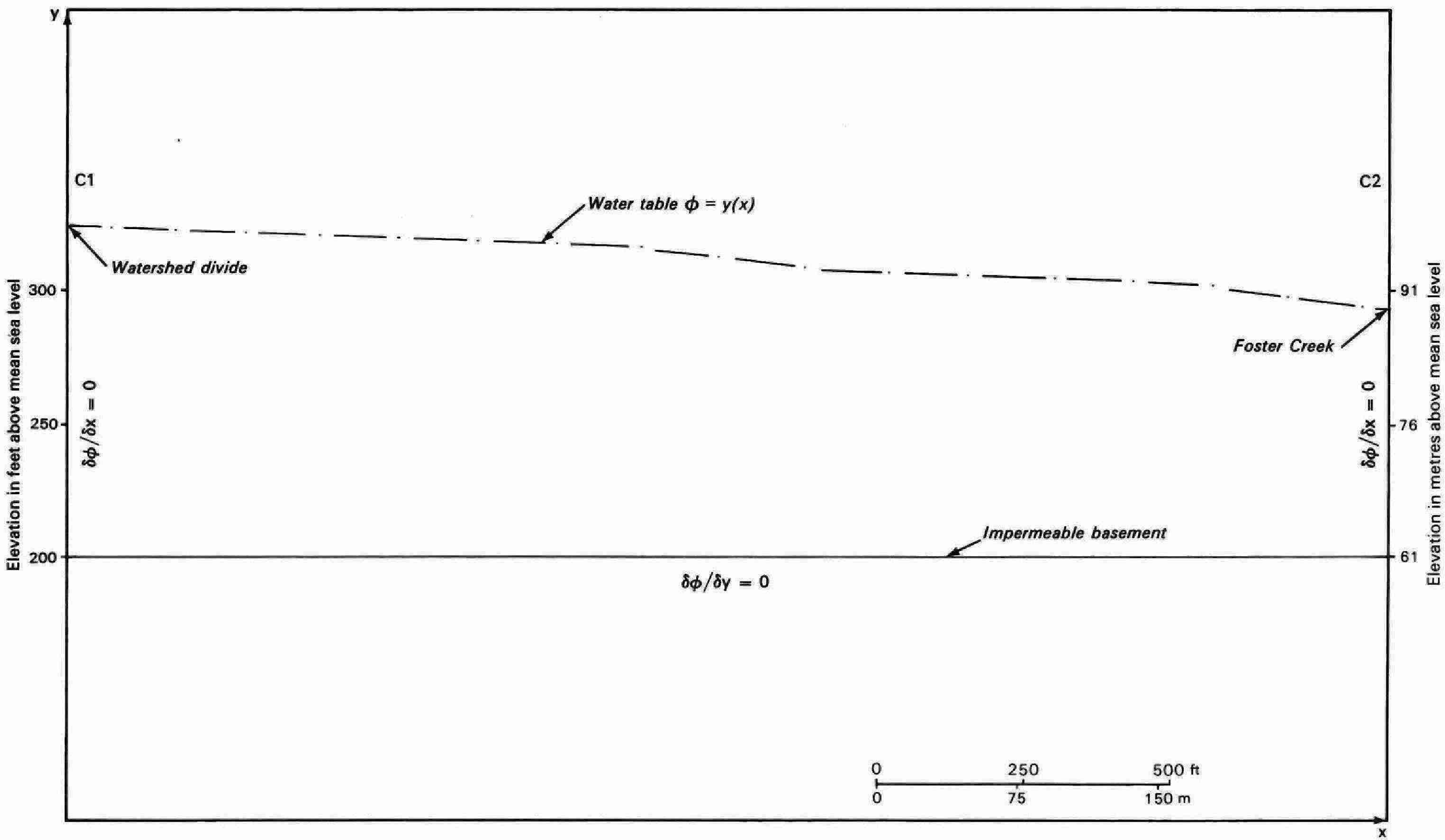

Figure 8. Boundary conditions assumed for the numerical solution of the potential distribution in the Newcastle section C1-C2.

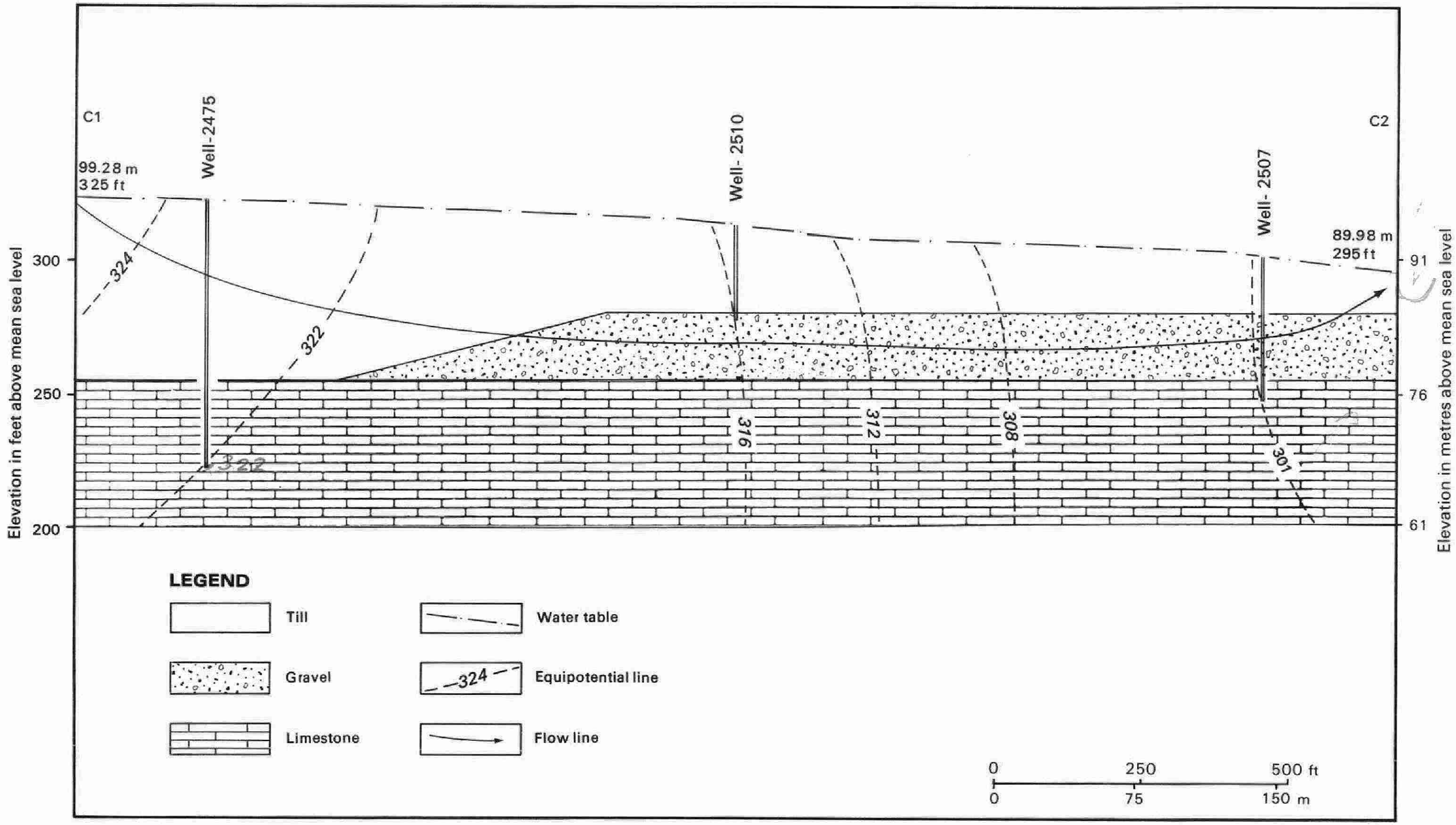

Figure 9. Steady-state potential distribution in the Newcastle section C1-C2 using linear triangular finite elements.

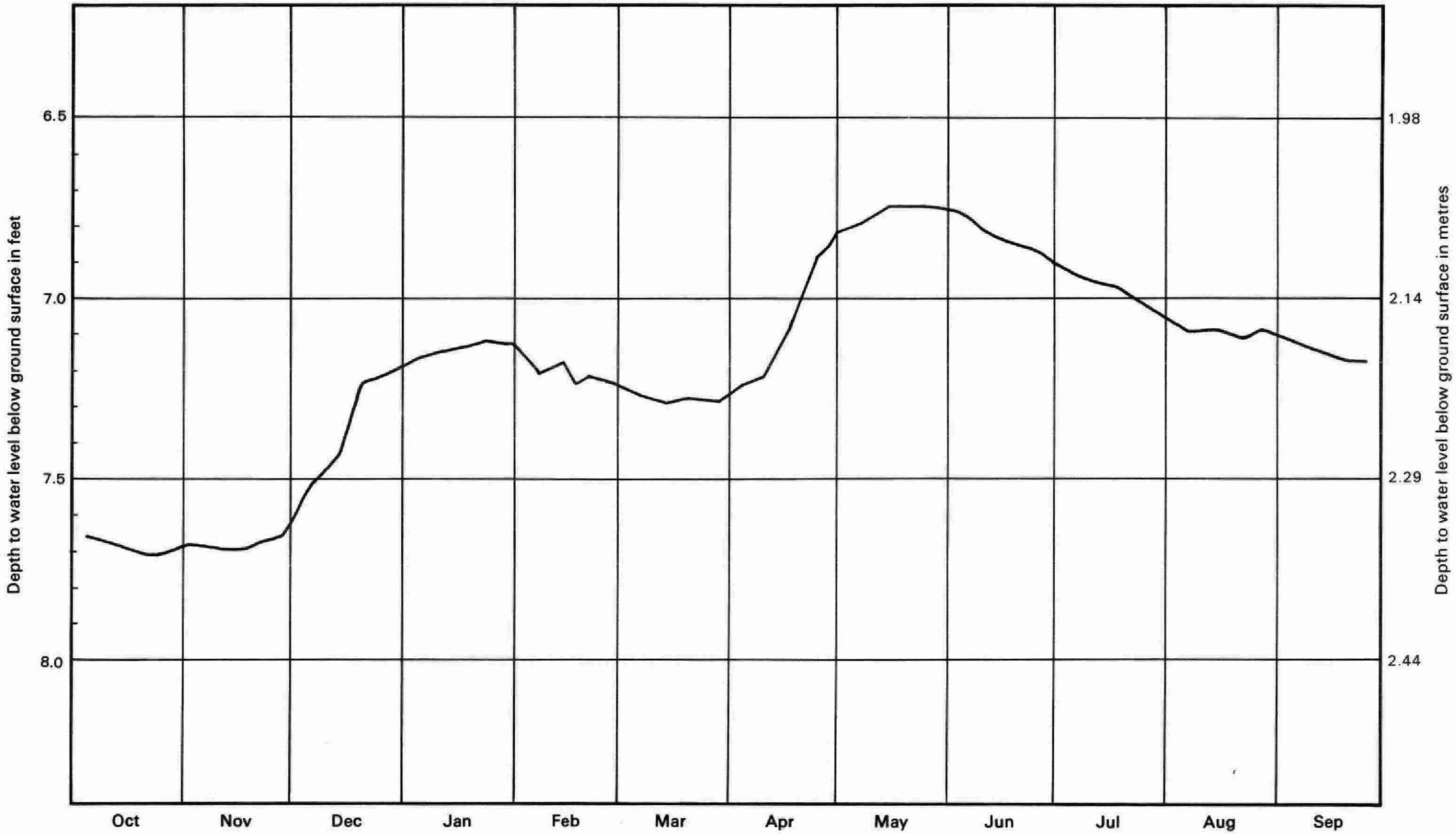

Figure 10. Hydrograph of water-level fluctuations in observation well B-4 A during the water-year 1971-1972.

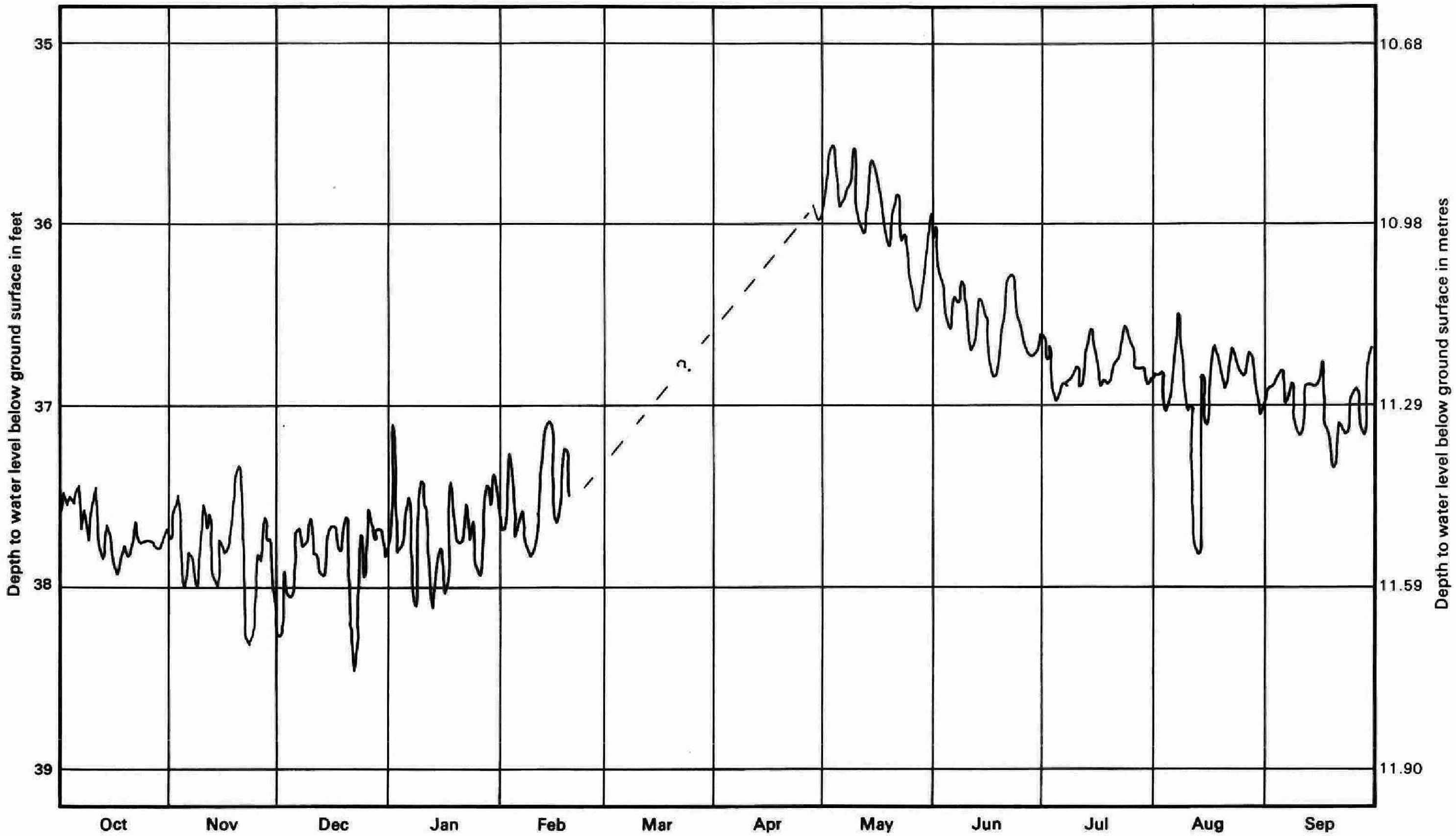

Figure 11. Hydrograph of water-level fluctuations in observation well S-7 during the water-year 1971-1972.

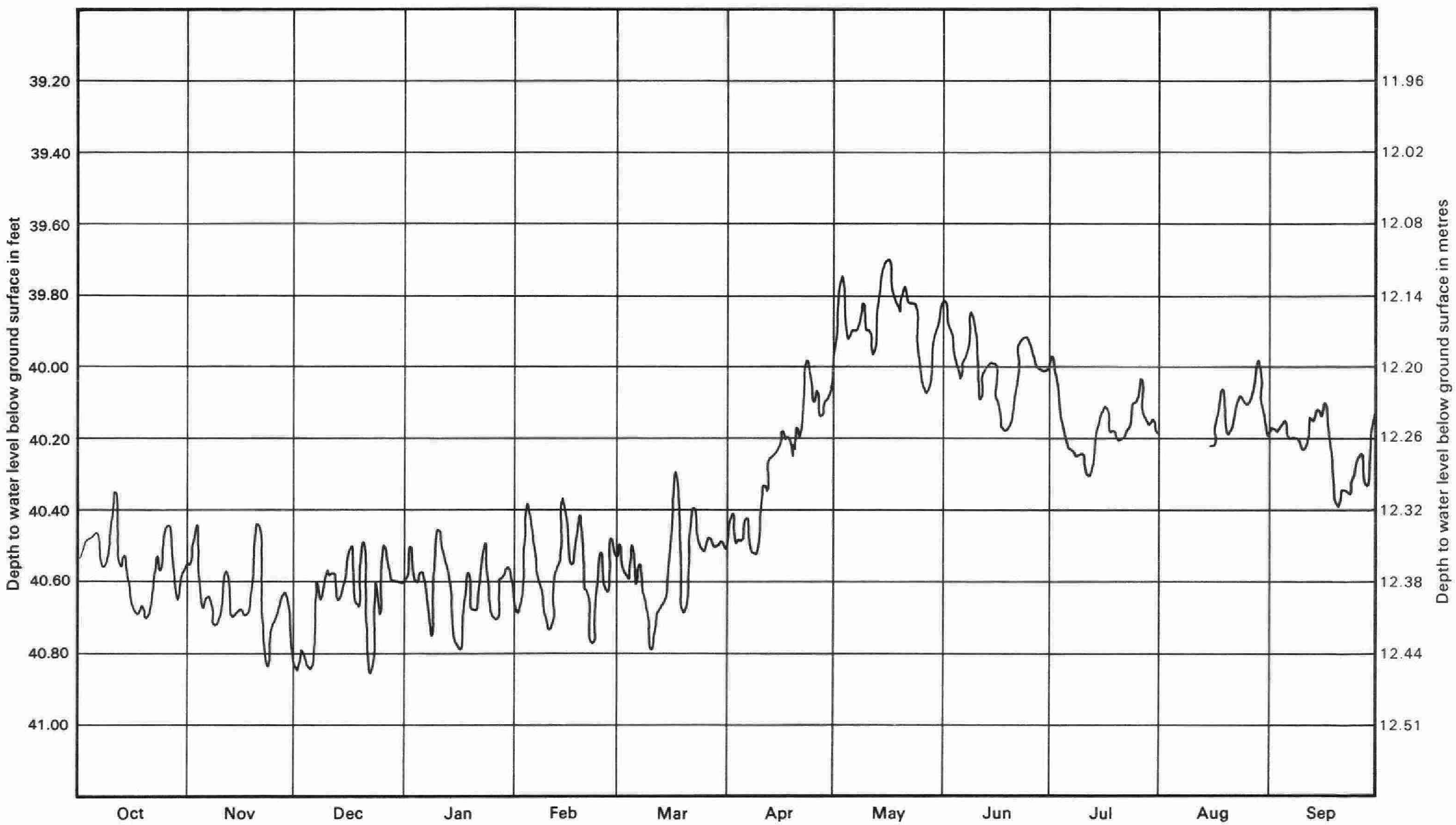

Figure 12. Hydrograph of water-level fluctuations in observation well W-3 during the water-year 1971-1972.

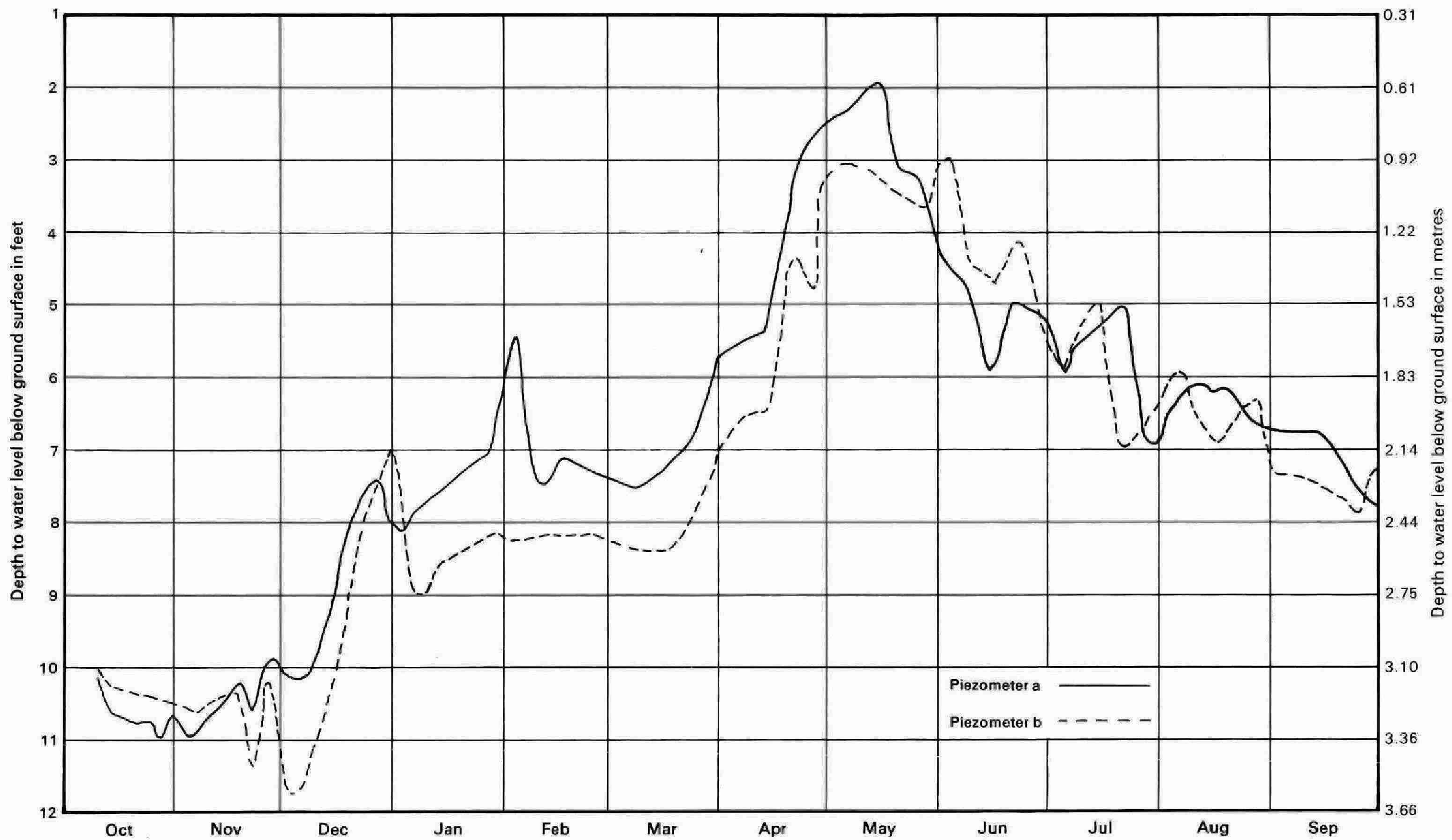

Figure 13. Hydrographs of water-level fluctuations in observation well W-5A (piezometers a and b) during water-year 1971-1972.

Figure 14. Hydrograph of water-level fluctuations in observation well W-5B during the water-year 1971-1972.

THE COEFFICIENTS OF PERMEABILITY, TRANSMISSIBILITY AND STORAGE

In dealing with quantitative ground-water investigations, two physical properties of the aquifer are of importance:

(i) The *coefficient of permeability*—defined as the rate of flow of water, in gallons per day, through a cross-sectional area of one square foot under a hydraulic gradient of one foot per foot, at a temperature of 60°F. Thus, the coefficient of permeability is a measure of the capacity of a material to transmit water, and multiplied by the thickness of the aquifer gives the coefficient of transmissibility. For the sake of convenience, the terms permeability and transmissibility will be used throughout this report rather than the coefficients of permeability or transmissibility.

(ii) The *coefficient of storage*—defined as the volume of water that is released from or taken into storage from a prism that has the same height as the aquifer and a surface area of one foot square, when the hydrostatic head normal to that surface is changed one foot.

Permeability and transmissibility values were determined for the study area using the following methods:

1. Pumping and recovery tests;
2. Grain-size distributions obtained from mechanical analyses;
3. Baseflow analyses.

In addition, a comparison was made between specific capacity values for those wells completed in the overburden and those completed in the bedrock indicating qualitatively, the relative transmissibility distributions in both materials.

Estimation of Transmissibility and Permeability from Pumping and Recovery Tests

Pumping and recovery tests generally give the most reliable results for determination of the hydrogeologic constants. By means of such tests, the constants are determined in situ, and no disturbance of the profile takes place.

Theis (1935) derived the nonequilibrium equation to determine the transmissibility of an aquifer. For a pumping test, the nonequilibrium equation is:

$$D = \frac{114.6Q}{T} \int_{1.56r^2S/Tt}^{\infty} \frac{e^{-u}}{u} du \tag{10}$$

where: D = drawdown, in feet, at any point of observation in the vicinity of a well discharging at a constant rate,
Q = discharge of the well, in gallons per minute,
T = transmissibility, in gallons per day per foot,
r = distance in feet, from the discharging well to the point of observation,
S = coefficient of storage, dimensionless,
t = time since pumping started,
u = 1.56 r^2S/Tt.

Jacob (1950) modified Equation 10 to the following form:

$$D = \frac{Q}{4\Pi T} \log_e \frac{2.25\ Tt}{r^2\ S} \tag{11}$$

In applying Equation 11 to measurements of the drawdown in a particular observation well, the distance r will be constant and it follows that the change in drawdown (ΔD) from time t_1 to t is:

$$\Delta D = D_2 - D_1 = \frac{2640Q}{T} \log_{10} \frac{t_2}{t_1} \tag{12}$$

For the recovery test, the Theis equation is given by:

$$D' = \frac{114.6Q}{T} \left(\int_{1.56r^2S/Tt}^{\infty} \frac{e^{-u}}{u} du - \int_{1.56r^2S/Tt}^{\infty} \frac{e^{-u}}{u} du \right) \tag{13}$$

in which: D = residual drawdown in feet,
Q = pumping rate in gallons per minute,
T = transmissibility in gallons per day per foot,
t = time since pumping began in minutes
t′ = time since pumping stopped in minutes,
r = distance to an observation well in feet,
S = the coefficient of storage during pumping and recovery, dimensionless,
$u = 1.56\ r^2S/Tt$.

If the coefficient of storage remains constant and $u = 1.56\ r^2S/Tt$ is sufficiently small, Equation 13 can be written as:

$$D' = \frac{2640Q}{T} \log_{10} \frac{t}{t'} \tag{14}$$

Data from 104 pumping and recovery tests are available from wells located within and in the vicinity of the study area. The duration of the pumping tests ranged from 1 to 12 hours. These data have been used to arrive at an estimate of the transmissibility of different types of deposits by applying equations 12 and 14.

The obtained values should be regarded as indicative of the magnitude rather than the absolute values of the transmissibilities for the following reasons:

(a) The data are related to the pumping wells themselves, no data are available for related observation wells.

(b) The duration of the pumping tests is short.

(c) The influence of partial penetration, screening method and friction losses accompanying the upward flow of water on the magnitude of drawdown were not taken into account. These factors cause additional drawdown in the wells and lower the obtained transmissibility values.

The estimated transmissibility values are given in tables 6, 7, 8, 9 and 10. The permeability values for the till, sand, shale and limestone were estimated by dividing the transmissibility by the thickness of the corresponding type of material.

Table 6. Estimated Transmissibility and Permeability Values from Short-Term Pumping and Recovery Tests for Wells Completed in the Overburden. Aquifer: Till

Well No.	Location (Zone 17)		Test	S.L.	Q	S.C.	T.	K.	Well Log	Aquifer
	Easting	Northing								
3247	675680	4869450	R	8	5	0.41	87	6.7	(0-1) soil, (1-21) till	till
3090	675040	4869190	R	17	10	0.20	660	66.0	(0-1) soil, (1-145) till	till
3253	674850	4869720	R	44	4	0.60	105	13.1	(0-1) soil, (1-52) till	till
2893	682950	4875080	P	10	10	1.00	377	31.4	(0-22) till	till
3100	682820	4874150	P	20	8	0.60	176	11.7	(0-1) soil, (1-10) clay, (10-35) till	till
3152	677560	4871530	R	18	6	0.30	80	3.5	(0-1) soil, (1-41) till	till
3188	677400	4871100	R	12	15	1.90	495	30.9	(0-1) soil, (1-8) till, (8-10) clay, (10-28) till	till
2739	674750	4872050	R	11	28	2.00	672	35.3	(0-1) soil, (1-30) till	till
2856	674950	4871450	R	30	3	0.30	72	6.0	(0-1) soil, (1-42) till	till
3223	674680	4872300	P	80	20	0.30	150	37.5	(0-219) till	till
3533	700850	4864250	R	15	3	0.15	113	9.4	(0-1) soil, (1-15) clay, (15-37.5) till	till
3115	695890	4865690	P	21	10	0.33	75	2.4	(0-1) soil, (1-52.5) till	till
3114	695900	4865670	P	20	9	0.30	77	2.3	(0-1) soil, (1-53) till	till
3112	695900	4865600	P	20	10	0.28	165	5.5	(0-1) soil, (1-50) till	till
3116	695890	4865700	P	21	8	0.25	75	2.3	(0-1) soil, (1-53) till	till
2821	695820	4865900	P	65	10	0.33	188	1.6	(0-2) soil, (2-179) till	till
3239	697140	4866540	R	5	7	0.22	108	3.3	(0-1) soil, (1-11) clay, (11-37.5) till	till
3117	683520	4871950	P	17	8	0.84	235	16.9	(0-1) soil, (1-31) till	till
2805	676700	4864360	P	20	4	0.10	55	1.1	(0-4) sand, (4-68) till	till
3119	681010	4863750	R	18	4	0.40	70	6.4	(0-1) soil, (1-29) till	till
2695	680840	4861770	R	8	6	0.40	59	3.4	(0-1) soil, (1-25) till	till
3118	691500	4869065	R	15	4	0.30	56	4.3	(0-1) soil, (1-28) till	till
3248	676200	4867940	R	6	2	0.20	75	5.0	(0-1) soil, (1-21) till	till
2985	676240	4868120	R	4	5	0.25	57	2.7	(0-6) clay, (6-25) till	till
2699	677420	4866900	R	20	6	0.60	144	11.0	(0-1) soil, (1-33) till	till
3264	681475	4869350	R	6	6	0.37	79	4.6	(0-1) soil, (1-7) clay, (7-23) till	till
2986	681330	4869500	R	8	10	0.66	102	6.3	(0-24) till	till
2988	681850	4869630	R	10	10	0.45	125	5.4	(0-1) soil, (1-33) till	till
2857	682870	4869340	R	10	3	0.19	49	2.5	(0-1) soil, (1-10) clay, (10-29) till	till

2853	683700	4871000	R	10	3	0.20	38	2.4	(0-1) soil, (1-10) clay, (10-26) till	till
2979	680610	4871250	R	13	8	0.88	162	13.5	(0-4) sand, (4-25) till	till
3257	680650	4871320	R	8	4	0.36	81	6.8	(0-5) soil, (5-20) till	till
3258	680630	4871320	R	8	5	0.50	120	10.9	(0-3) soil, (3-19) till	till
2940	678540	4864920	R	15	1	0.08	17	1.4	(0-8) till, (8-15) clay, (15-27) till	till
2717	677850	4865200	R	12	3	0.37	61	5.5	(0-3) soil, (3-23) till	till
3041	676520	4864250	R	7	2	0.04	75	18.75	(0-1) soil, (1-7) sand, (7-65) till	till
3263	683570	4877450	R	12	5	0.60	73	9.1	(0-2) soil, (2-8) clay, (8-20) till	till
2983	678950	4874500	R	7	5	0.55	132	13.2	(0-1) soil, (1-17) till	till
2771	676700	4874600	R	54	4	0.50	132	9.4	(0-1) soil, (1-68) till	till
3199	676465	4875070	R	30	10	0.60	240	13.3	(0-1) soil, (1-25) clay, (25-47) till	till
2718	674880	4874480	R	25	4	0.80	117	11.7	(0-1) soil, (1-35) till	till
3261	675165	4874700	R	16	3	0.30	79	8.7	(0-1) soil, (1-16) clay, (16-25) till	till
2748	675930	4878040	R	35	5	0.10	60	1.7	(0-70) till	till
3265	673000	4876930	R	27	6	0.40	198	14.1	(0-1) soil, (1-41) till	till
3164	680730	4871050	R	8	8	0.61	140	10.7	(0-1) soil, (1-21) till	till
3094	691300	4868950	P	5	12	0.90	260	17.3	(0-1) soil, (1-20) till	till
3091	691365	4868950	P	6	7	1.00	308	38.5	(0-1) soil, (1-14) till	till
2970	693110	4871790	P	10	10	0.71	203	11.9	(0-27) till	till
3178	697800	4871250	P	8	8	0.72	350	29.3	(0-1) soil, (1-13) clay, (13-20) till	till
3250	691300	4866820	R	20	4	0.57	88	11.0	(0-1) soil, (1-12) till, (12-19) sand, (19-28) till	till
3176	691180	4866765	P	12	8	0.66	352	27.0	(0-1) soil, (1-25) till	till
3177	691240	4866765	P	10	7	0.50	184	12.2	(0-1) soil, (1-25) till	till
3193	691140	4866780	P	10	8	0.66	352	23.4	(0-1) soil, (1-25) till	till
2978	680400	4871460	R	11	8	0.80	176	16.0	(0-4) sand, (4-22) till	till
2977	680550	4871210	R	14	10	1.00	202	18.3	(0-5) sand, (5-25) till	till
3228	683540	4871940	P	23	20	0.40	195	4.8	(0-63) till	till
3117	683520	4871950	P	17	8	0.60	211	15.0	(0-1) soil, (1-31) till	till
2984	674140	4872000	R	28	4	0.50	75	8.3	(0-1) soil, (1-37) till	till
3183	682640	4868545	R	18	8	2.70	704	17.6	(0-15) till, (15-18) sand, (18-22) till	till

Test—Type of Test: P—Pumping, R—Recovery
S.L. —Static Level (ft.)
Q. —Pumping Rate (IGPM)
S.C.—Specific Capacity (IGPM/ft.)
T. —Estimated Transmissibility (IGPD/ft.)
K. —Estimated Permeability ($IGPD/ft.^2$)

Table 7. Estimated Transmissibility Values from Short-Term Pumping or Recovery Tests for Wells Completed in the Overburden. Aquifer: Till and Sand or Till and Gravel

Well No.	Location (Zone 17)		Test	S.L.	Q	S.C.	T.	K.	Well Log	Aquifer
	Easting	Northing								
3196	696600	4870670	R	8	4	0.44	176		(0-1) soil, (1-8) till, (8-17) gravel	till & gravel
2948	702250	4868690	P	14	10	1.00	440		(0-16) clay, (16-19) sand & gravel, (19-25) till	till, sand & gravel
2818	690570	4868600	P	30	7	1.75	616		(0-2) soil, (2-42) till, (42-43) coarse sand	till & sand
3281	701075	4870700	P	5	15	1.00	247		(0-1) soil, (1-10) sand, (10-15) sand & silt	sand & silt
3147	674760	4872020	R	20	24	6.00	1056		(0-20) till, (20-21) sand, (21-25) till	till & sand
3255	675400	4870230	R	5	8	0.90	132		(0-1) soil, (1-10) till, (10-13) sand, (13-16) till	till & sand
3382	674900	4869375	R	37	10	0.23	165		(0-2) soil, (2-33) clay, (33-57) gravel, (57-101) till, (101-106) gravel	till & gravel
2808	676480	4864300	R	5	4	0.19	176		(0-1) soil, (1-31) till, (31-32) sand	till & sand
3160	696000	4865380	P	50	13	0.68	343		(0-1) soil, (1-55) till, (55-62) sand & gravel	till, sand & gravel
3158	695890	4865720	P	40	15	1.25	660		(0-1) soil, (1-15) clay, (15-45) till, (45-54) sandy gravel	till & gravel
2980	677250	4866110	R	16	10	0.76	220		(0-1) soil, (1-12) till, (12-15) sand, (15-29) till, (29-30) gravel	till & gravel
3171	700750	4876050	P	21	7	0.63	261		(0-1) soil, (1-27) sand, (27-32.5) till	till & sand
2931	691250	4869120	R	20	15	1.07	264		(0-1) soil, (1-25) clay, (25-38) till, (38-40) gravel	till & gravel
2929	691000	4869730	R	4	10	0.17	188		(0-1) soil, (1-8) till, (8-20) clay, (20-21) sand	till, clay & sand
2838	691100	4869700	R	12	10	0.58	94		(0-1) soil, (1-16) till, (16-27) sand, (27-32) clay	till, sand & clay
2820	683280	4869900	P	30	10	0.40	377		(0-2) soil, (2-47) till, (47-61) sand, (61-65) till	till & sand
2932	691950	4864140	R	21	15	1.00	172		(0-1) soil, (1-15) clay, (15-16) sand, (16-30) till, (30-31) sand, (31-32.5) till	till & sand

Test—Type of Test: P—Pumping, R—Recovery
S.L. —Static Level (ft.)
Q. —Pumping Rate (IGPM)
S.C.—Specific Capacity (IGPM/ft.)
T. —Estimated Transmissibility (IGPD/ft.)
K. —Estimated Permeability (IGPD/ft.^{2})

Table 8. Estimated Transmissibility Values from Short-Term Pumping or Recovery Tests for Wells Completed in the Overburden. Aquifer: Till and Clay

Well No.	Location (Zone 17)		Test	S.L.	Q	S.C.	T.	K.	Well Log	Aquifer
	Easting	Northing								
3166	679000	4864930	R	8	5	0.22	44		(0-4) sand, (4-12) clay, (12-30) till	till & clay
3280	684200	4875475	P	15	25	0.80	130		(0-1) soil, (1-12) till, (12-50) clay, (50-53) till	till & clay
3195	701170	4865530	R	16	4	0.36	81		(0-1) soil, (1-16) clay, (16-20) sand, (20-27.5) clay	clay & sand
3105	690620	4867840	R	17	2	0.16	33		(0-1) soil, (1-8) clay, (8-28) till, (28-29) clay	till & clay
2830	685200	4871640	R	28	2	0.07	53		(0-1) soil, (1-42) till, (42-55) clay	till & clay
3249	681200	4870835	R	7	3	0.23	53		(0-1) soil, (1-12) till, (12-21) clay	till & clay
3251	680455	4871440	R	6	2	0.08	44		(0-2) soil, (2-6) clay, (6-24) till, (24-30) clay	till & clay
2844	685390	4871830	P	40	10	0.20	44		(0-1) soil, (1-85) till, (85-115) clay, (115-122) till	till & clay
2951	685850	4872000	R	8	10	0.43	90		(0-1) soil, (1-8) sand, (8-12) clay, (12-30) till, (30-34) clay, (34-41) till	till & clay

Test—Type of Test: P—Pumping, R—Recovery
S.L. —Static Level (ft.)
Q. —Pumping Rate (IGPM)
S.C. —Specific Capacity (IGPM/ft.)
T. —Estimated Transmissibility (IGPD/ft.)
K. —Estimated Permeability (IGPD/ft.^{2})

Table 9. Estimated Transmissibility and Permeability Values from Short-Term Pumping and Recovery Tests for Wells Completed in the Overburden. Aquifer: Sand

Well No.	Location (Zone 17)		Test	S.L.	Q	S.C.	T.	K.	Well Log	Aquifer
	Easting	Northing								
3276	683040	4871200	R	37	10	0.20	1320	377.0	(0-2) soil, (2-90) till, (90-93.5) sand, (93.5-97) till	sand
2837	700800	4867850	R	7	8	0.72	528	35.2	(0-1) soil, (1-22) sand	sand
2966	701520	4871670	P	10	10	0.77	377	25.1	(0-1) soil, (1-25) sand	sand
2839	691400	4869050	R	4	8	0.72	162	11.5	(0-1) soil, (1-17) sand	sand
2930	680850	4867280	R	4	5	0.60	110	11.0	(0-14) sand	sand
3242	700700	4867730	R	34	6	0.85	396	49.5	(0-1) soil, (1-13) clay, (13-34) till, (34-42) sand	sand
3157	695860	4865750	P	44	14	1.75	1848	184.8	(0-1) soil, (1-15) clay, (15-30) till, (30-45) clay, (45-55) sand	sand
3004	677940	4879950	P	70	10	0.30	80	20.0	(0-112) till, (112-117) sand	sand
3262	673505	4876050	R	10	10	0.66	264	17.6	(0-1) soil, (1-10) clay, (10-25) sand	sand

Test—Type of Test: P—Pumping, R—Recovery
S.L. —Static Level (ft.)
Q. —Pumping Rate (IGPM)
S.C.—Specific Capacity (IGPM/ft.)
T. —Estimated Transmissibility (IGPD/ft.)
K. —Estimated Permeability (IGPD/ft.^{2})

Table 10. Estimated Transmissibility and Permeability Values from Short-Term Pumping and Recovery Tests for Wells Completed in the Bedrock. Aquifer: Limestone or Shale

Well No.	Location (Zone 17)		Test	S.L.	Q	S.C.	T.	K.	Well Log	Aquifer
	Easting	Northing								
3341	686175	4869000	R	47	4	0.20	151	38.0	(0-2) soil, (56-76) clay, (76-80) limestone	limestone
3322	691525	4869000	R	68	1	0.02	4	0.1	(0-2) soil, (2-12) clay, (12-77) till, (77-128) limestone	limestone
3169	692740	4866820	P	30	4	0.01	34	5.7	(0-8) soil, (8-82) till, (82-90) limestone	limestone
3340	696450	4868675	R	8	3	0.02	5	0.3	(0-2) soil, (2-40) till, (40-109) sand & gravel, (109-114) clay, (114-129) limestone	limestone
3086	692040	4869130	P	40	8	0.10	22	1.2	(0-96) till, (96-114) limestone	limestone
3005	682160	4869200	P	7	10	0.15	27	4.5	(0-15) previously dug, (15-78) till, (78-84) limestone	limestone
2833	684550	4864100	R	70	2	0.01	3	0.02	(0-156) till, (156-295) black shale	shale

Test—Type of Test: P—Pumping, R—Recovery
S.L. —Static Level (ft.)
Q. —Pumping Rate (IGPM)
S.C.—Specific Capacity (IGPM/ft.)
T. —Estimated Transmissibility (IGPD/ft.)
K. Estimated Permeability (IGPD/$ft.^2$)

Table 11. Estimated Transmissibility of the Overburden Based on the Average Permeability Values Obtained from Pumping and Recovery Tests for Various Types of Deposits

Well No.	Location (Zone 17) Easting	Location (Zone 17) Northing	Well Depth (ft.)	S.L. (ft.)	T.S.TH. (ft.)	O.S.TH. (ft.)	E.TR. (IGPD/ft.)	Well Log
1117	692759	4863146	100	54	46	39	603	(0-93) till, (93-100) bedrock
1113	692493	4863959	96	25	71	67	4228	(0-40) clay, (40-92) sand, (92-96) bedrock
1177	689683	4871159	115	5	110	105	4065	(0-60) clay, (60-110) sand, (110-115) bedrock
1176	689460	4870352	155	20	135	119	1840	(0-139) till, (139-155) bedrock
1174	689492	4870194	177	65	112	107	1554	(0-22) till, (22-35) gravel, (35-92) till, (92-98) sand, (98-140) till, (140-145) bedrock
1260	690313	4868088	263	102	161	79	1221	(0-15) clay, (15-181) till, (181-263) bedrock
1111	691126	4864208	110	10	100	20	309	(0-30) till, (30-110) bedrock
1100	690746	4865006	40	7	33	23	78	(0-25) clay, (25-30) till, (30-40) bedrock
1101	690269	4864838	127	58	69	68	1051	(0-126) till, (126-127) bedrock
1394	689381	4865823	241	75	166	165	2551	(0-240) till, (240-241) bedrock
1079	686550	4861600	28	12	16	14	216	(0-26) till, (26-28) bedrock
1092	691164	4866301	84	12	72	26	402	(0-38) till, (38-84) bedrock
45	686938	4870153	61	16	45	34	695	(0-28) till, (28-30) sand, (30-50) till, (50-61) bedrock
1203	687720	4868051	130	28	102	91	650	(0-24) previously dug, (24-60) clay, (60-102) till, (102-119) clay, (119-130) bedrock
1083	689930	4866253	100	10	90	19	294	(0-29) till, (29-100) bedrock
1495	688714	4862740	252	72	180	175	2705	(0-38) sand, (38-247) till, (247-252) bedrock
19	684917	4871154	30	0	30	25	387	(0-25) till, (25-30) bedrock
32	684915	4871154	39	3	36	31	479	(0-34) till, (34-39) bedrock
34	685053	4871116	26	6	20	18	278	(0-24) till, (24-26) bedrock
16	685452	4870205	50	18	32	7	108	(0-25) till, (25-50) bedrock
44	685150	4865635	117	17	100	99	1530	(0-116) till, (116-117) bedrock
1489	686885	4862767	204	40	164	163	3639	(0-63) till, (63-80) sand, (80-203) till, (203-204) bedrock
38	683829	4869205	47	12	35	21	325	(0-33) till, (33-47) bedrock
1149	684047	4867152	127	14	113	84	3831	(0-33) till, (31-59) sand, (59-64) till, (64-74) gravel, (74-98) till, (98-127) bedrock
1481	685193	4861310	104	15	89	84	1298	(0-99) till, (99-104) bedrock
1198	684372	4865040	116	20	96	80	1452	(0-5) till, (5-35) sand, (35-50) till, (50-100) clay, (100-116) bedrock
1384	684383	4864729	310	21	289	54	4390	(0-14) clay, (14-75) sand, (75-310) bedrock
1480	684209	4861884	147	26	121	90	4486	(0-73) sand, (73-116) till, (116-147) bedrock

1144	682886	4866713	64	0	64	63	1369	(0-57) till, (57-63) sand, (63-64) bedrock
1196	683467	4865355	125	12	113	62	2210	(0-21) sand, (21-64) till, (64-74) sand, (74-125) bedrock
1139	681788	4868241	146	20	126	96	1616	(0-38) till, (38-40) sand, (40-116) till, (116-146) bedrock
744	681950	4866898	118	18	100	80	1237	(0-98) till, (98-118) bedrock
685	691213	4864460	107	10	97	81	1252	(0-91) till, (91-107) bedrock
742	690906	4864687	123	36	87	77	1190	(0-113) till, (113-123) bedrock
798	681510	4866390	118	28	90	51	4146	(0-23) till, (23-79) sand, (79-118) bedrock
851	682094	4862952	116	20	96	95	1930	(0-108) till, (108-115) sand, (115-116) bedrock
850	682104	4862758	142	40	102	84	1299	(0-124) till, (124-142) bedrock
934	682793	4860796	214	57	157	109	3265	(0-81) sand, (81-166) till, (166-214) bedrock
675	692936	4863942	55	18	37	34	526	(0-52) till, (52-55) bedrock
778	691535	4868930	65	24	41	30	464	(0-54) till, (54-65) bedrock
680	692586	486924	67	20	47	43	665	(0-63) till, (63-67) bedrock
730	692495	4865071	79	12	65	61	278	(0-30) till, (30-73) clay, (73-79) bedrock
727	691827	4866858	127	30	97	40	618	(0-70) till, (70-127) bedrock
2502	693840	4864357	53	18	35	32	1626	(0-30) clay, (30-50) sand & gravel, (50-53) bedrock
722	692836	4866731	88	48	40	24	634	(0-25) clay, (25-68) till, (68-72) sand, (72-88) bedrock
770	692390	4867982	193	23	170	80	1236	(0-10) sand, (10-103) till, (103-193) bedrock
764	692420	4867973	108	40	68	66	1020	(0-106) till, (106-108) bedrock
879	691231	4871879	156	30	136	120	1855	(0-150) till, (150-156) bedrock
2501	693800	4865054	74	16	58	54	3468	(0-30) till, (30-70) sand, (70-74) bedrock
826	691877	4869974	150	40	110	82	535	(0-60) till, (60-63) sand, (63-122) clay, (122-150) bedrock
820	691512	4871159	138	36	102	96	4513	(0-82) sand, (82-132) till, (132-138) bedrock
714	695803	4868100	155	13	142	138	4043	(0-42) sand, (42-151) till, (151-155) bedrock
716	695710	4866088	173	50	123	122	1951	(0-171) till, (171-172) gravel, (172-173) bedrock
2475	694078	4865472	102	20	82	53	819	(0-73) till, (73-102) bedrock
728	692526	4864960	68	28	40	32	495	(0-60) till, (60-68) bedrock
742	690906	4864687	123	36	87	77	1190	(0-113) till, (113-123) bedrock
1139	681788	4868241	146	20	126	96	1484	(0-116) till, (116-146) bedrock
1167	688060	4868859	138	26	112	111	1816	(0-134) till, (134-137) gravel, (137-138) bedrock
1252	690042	4868877	280	20	260	140	2494	(0-60) till, (60-65) sand, (65-160) till, (160-260) bedrock

Sample No. = 59 items
Estimated Mean Transmissibility of the Overburden = 1626 IGPD/ft.
S.L.—Static Level, T.S.TH.—Total Saturated Thickness, O.S.TH.—Overburden Saturated Thickness
E.TR.—Estimated Transmissibility.

The estimated permeability values for the till deposits in the study area ranged from 1 to 66 IGPD/ft^2 with an average value of 15 IGPD/ft^2. The peremeability of the sand ranges from 11 to 377 IGPD/ft^2, with an average value of 81 IGPD/ft^2. The permeability of the limestone ranges from 0.1 to 38 IGPD/ft^2, with an average value of 8 IGPD/ft^2. Only one value is available for the permeability of shale and equals 0.02 IGPD/ft^2.

The mean values of the permeability of the till, sand, limestone and the one value for the shale obtained from pumping and recovery tests were used to estimate the total transmissibility of the overburden and the upper 50 feet of the bedrock. Logs of wells completed in the bedrock were used for these estimations. Only the saturated thickness of the overburden was considered and the transmissibility at each well location was calculated by multiplying the saturated thickness of each type of deposit by its mean permeability and summing up the results. Estimated values of the transmissibilities of the overburden are given in Table 11 which indicates that the mean transmissibility of the overburden within the study area is about 1600 IGPD/ft. Assuming that the mean permeability of the bedrock (shale and limestone) is about 4 IGPD/ft^2, the mean transmissibility of the upper 50 feet of the bedrock will be 200 IGPD/ft, whereas, the mean transmissibility of the overburden and the upper 50 feet of the bedrock is estimated to be about 1800 IGPD/ft. The values given above should be regarded as indicative of the magnitude of the mean transmissibility encountered within the study area. The transmissibility in one particular location could be completely different from that obtained from the mean permeability values assigned to various types of deposits. In addition, the transmissibility at one location is not constant, but is a function of the fluctuations of the ground-water levels with time.

Estimation of the Permeability of the Sand Outcropping in Bluffs along the Shoreline of Lake Ontario by Using Grain-Size Distributions Obtained from Mechanical Analyses

Many attempts have been made to calculate the permeability of sand samples from grain-size analyses (i.e. from the mechanical analyses curves). One formula that demonstrates the relation between permeability and the grain size has the form:

$$K = \alpha d^2 \qquad (15)$$

where: K = permeability,
d = grain size
α = proportionality coefficient.

In this formula the proportionality coefficient α varies strongly from one case to another, depending on grain-size distribution, shape of the grains, porosity of the aquifer and the viscosity of the percolating ground water. According to Hazen, (Huisman, 1969), however, a good average for natural sands is given by:

$$K = (11)\,10^3\,(d_{10})^2 \qquad (16)$$

where: K = permeability expressed in m/sec., (X 1.77x10^6) IGPD/ft^2
d_{10} = the effective size which is defined as the particle size where 10 percent of the sand is finer and 90 percent is coarser and expressed in metres.

Sixteen samples of sand were collected for mechanical analyses from the sand beds that outcrop in the bluffs. Ten of these samples represent the Clarke sands, whereas, the rest were

collected from the sand and silt beds associated with the Upper Glacial Unit. The results of the mechanical analyses are given in Table 12, and the grain-size curves are illustrated in figures 15 and 16.

Table 12. Results of Mechanical Analyses of the Clarke Sands and the Sands and Silts Associated with the Upper Glacial Unit

Sample No.	Sand %	Silt %	Clay %	Material
14	75.0	25.0	0.0	Clarke sand
15	82.0	18.0	0.0	Clarke sand
18	84.0	16.0	0.0	Clarke sand
20	87.0	13.0	0.0	Clarke sand
22	88.0	12.0	0.0	Clarke sand
24	72.0	38.0	0.0	Clarke sand
34	95.0	5.0	0.0	Clarke sand
34-A	84.0	16.0	0.0	Clarke sand
85	84.0	16.0	0.0	Clarke sand
93	84.0	16.0	0.0	Clarke sand
6	62.0	38.0	0.0	sand of the Upper Glacial Unit
40	17.0	83.0	0.0	silt of the Upper Glacial Unit
41	23.0	77.0	0.0	silt of the Upper Glacial Unit
61	40.0	60.0	0.0	silt of the Upper Glacial Unit
63	9.0	83.0	8.0	silt of the Upper Glacial Unit
75	51.0	49.0	0.0	silt-sand of the Upper Glacial Unit

Grain size in millimeters

Clay: <0.004
Silt: 0.004—0.06
Sand: 0.06—2.00

As was described earlier, the Clarke sands consist of well-sorted, very fine sands, whereas the stratified deposits associated with the Upper Glacial Unit consist mainly of silt and very fine sand.

Equation 16 was applied to estimate the permeability of both types of deposits. The results are given in tables 13 and 14 and indicate that the permeability of the Clarke sands ranges from 28 to 124 IGPD/ft^2, with an average of approximately 56 IGPD/ft^2. The permeability of the sand of the Upper Glacial Unit ranges from 4 to 15 IGPD/ft^2 with an average value of approximately 8 IGPD/ft^2. These results are compatible with those obtained from the pumping and recovery tests, where the permeability of the sand was estimated to range from 11 to 377 IGPD/ft^2.

Table 13. Estimated Permeability of the Clarke Sands Based on Grain-Size Analyses

Sample No.	Coefficient of Uniformity d_{60}/d_{10}	Effective Size (d_{10}) in m.	$(d_{10})^2$	K in IGPD/ft.^{2}
14	2.6	45×10^{-6}	2025×10^{-12}	39.0
15	2.7	52×10^{-6}	2704×10^{-12}	53.0
18	3.0	50×10^{-6}	2500×10^{-12}	49.0
20	2.3	65×10^{-6}	4225×10^{-12}	82.0
22	2.0	63×10^{-6}	3969×10^{-12}	77.0
24	3.1	38×10^{-6}	1444×10^{-12}	28.0
34	2.5	80×10^{-6}	6400×10^{-12}	124.0
34-A	2.2	55×10^{-6}	3025×10^{-12}	59.0
85	2.3	55×10^{-6}	3025×10^{-12}	59.0
93	3.0	50×10^{-6}	2500×10^{-12}	49.0

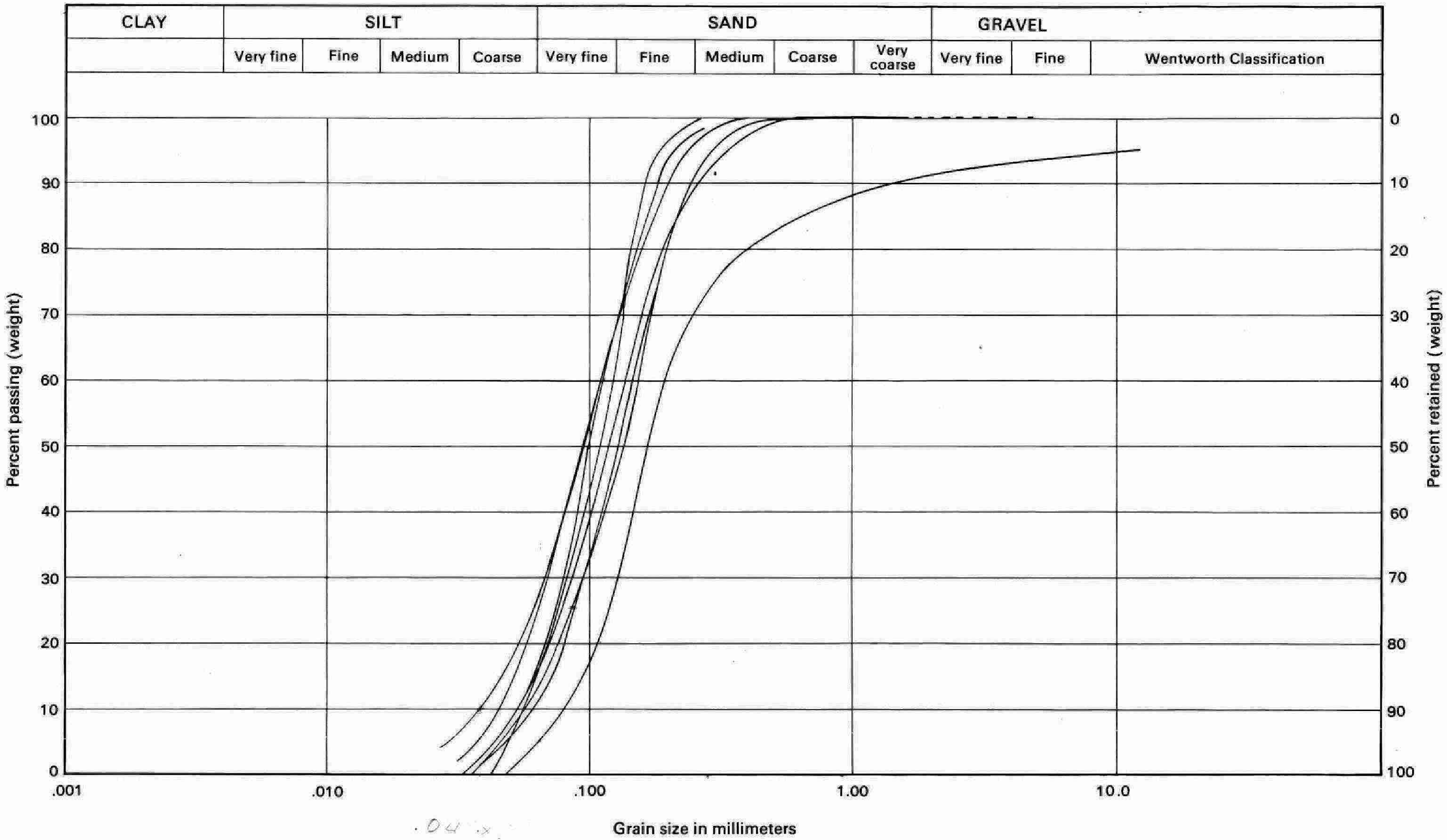

Figure 15. Grain-size distributions of the Clarke sands.

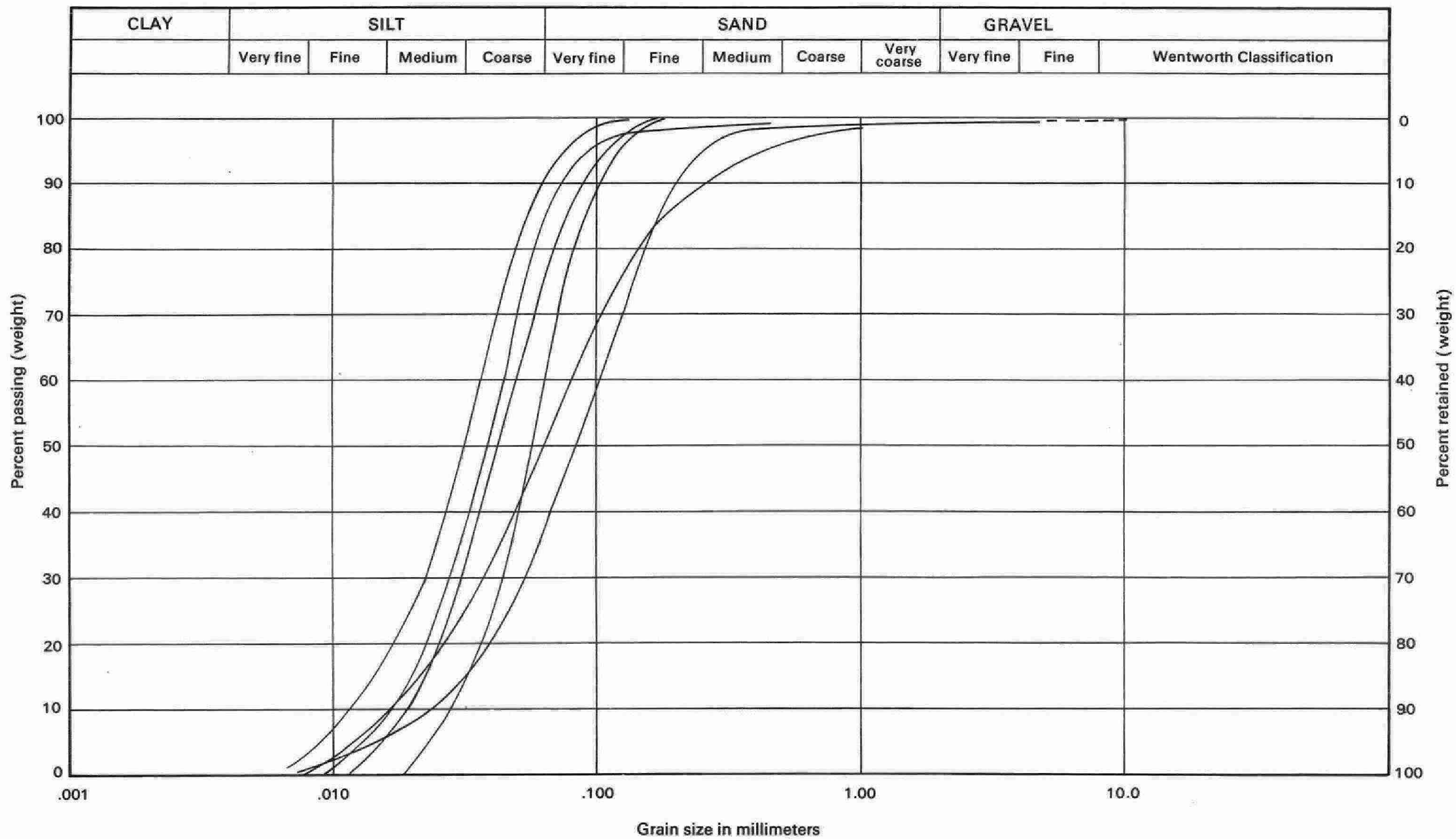

Figure 16. **Grain-size distributions of the silts and sands associated with the Upper Glacial Unit.**

Table 14. **Estimated Permeability of the Sands and Silts of the Upper Glacial Unit Based on Grain-Size Analyses**

Sample No.	Coefficient of Uniformity d_{60}/d_{10}	Effective Size (d_{10}) in m.	$(d_{10})^2$	K in IGPD/ft.^{2}
6	3.0	25×10^{-6}	625×10^{-12}	12.0
40	2.5	18×10^{-6}	324×10^{-12}	6.0
41	2.6	19×10^{-6}	361×10^{-12}	7.0
61	2.3	28×10^{-6}	784×10^{-12}	15.0
63	2.9	13×10^{-6}	169×10^{-12}	4.0
75	3.2	19×10^{-6}	361×10^{-12}	7.0

Estimation of Transmissibility from Baseflow Analyses

The average transmissibility was estimated for both the Bowmanville and Wilmot creeks basins by applying Darcy's Law:

$$Q_{av} = 2\ TIL \qquad (17)$$

where: Q_{av} = the mean baseflow discharge,
T = the average transmissibility,
I = the average water-table slope,
L = the creek length.

The creek length L was computed from topographic maps, scale: 1/25,000, published by the Department of Energy, Mines and Resources in 1969. The average water-table slope was considered to be equal to 0.02 feet per foot, based on the water-level contours from existing water-well data. The transmissibility value obtained by using this method is indicative of the average value because all the terms Q_{av}, I and L are estimates.

For Bowmanville Creek:
Q_{av} = 23.5 cfs (see baseflow analysis),
L = 45 miles,
I = 0.02 dimensionless,
$T \approx$ 1300 IGPD/ft.

For Wilmot Creek:
Q_{av} = 18 cfs,
L = 36 miles,
I = 0.02 dimensionless,
$T \approx$ 1300 IGPD/ft.

The average transmissibility values obtained largely represent the transmissibility of the overburden. These results are in fair agreement with the average transmissibility value obtained from pumping and recovery tests which was determined to be about 1600 IGPD/ft. for the overburden.

A Comparison Between Specific Capacity Values for Wells Completed in the Overburden and Wells Completed in the Bedrock

The specific capacity of a well is defined as its yield per unit of drawdown, expressed as gallons per minute per foot of drawdown. Dividing the yield by the drawdown for a specific time during a pump test, gives the value of the specific capacity.

The specific capacity of a well is a function of the type of aquifer, well diameter, pumping time, partial penetration, hydrogeological boundaries, and man-made factors. Because of the above-mentioned reasons, the specific capacity is not an exact criterion with which to estimate transmissibility; however, high specific capacities are generally indicative of high transmissibilities.

Specific capacity data for wells completed in the overburden and wells completed in the bedrock, which have common radii and pumping periods were compared. Specific capacities for both types of wells were tabulated in order of magnitude, and frequencies were computed using the formula:

$$P = \frac{n}{m+1} \tag{18}$$

where: P = probability,
n = order number of the items arranged in ascending magnitude; thus $n=1$ for the smallest item,
m = total number of items.

Values of specific capacity were then plotted against percent of wells, on logarithmic probability paper (Figure 17). The specific capacity values for the overburden as well as for the bedrock plot as approximately straight lines on the logarithmic probability paper, indicating that both samples have a lognormal frequency distribution.

On the log-probability plots (Figure 17), the arithmetic mean $\bar{X}$ equals X_{50} which is the specific capacity value at the 50 percent probability level. The standard deviation is determined from the log-probability plots as:

$$\sigma = \frac{1}{2}(X_{16} - X_{84}) \tag{19}$$

where: X_{16}, X_{84} = the specific capacity values at the 16 percent and 84 percent probability levels.

A comparison between the specific capacity frequency graphs of the overburden and the bedrock indicate that the productivity of the overburden deposits is higher than that of the bedrock. The arithmetic mean for the overburden specific capacity values is 0.49 IGPD/ft., whereas, for the bedrock it is 0.008 IGPD/ft. On the other hand, the standard deviation for the overburden is 0.780 IGPD/ft. which is almost four times larger than that of the bedrock which equals 0.202 IGPD/ft. This indicates that the bedrock formations are more uniform than the overburden deposits.

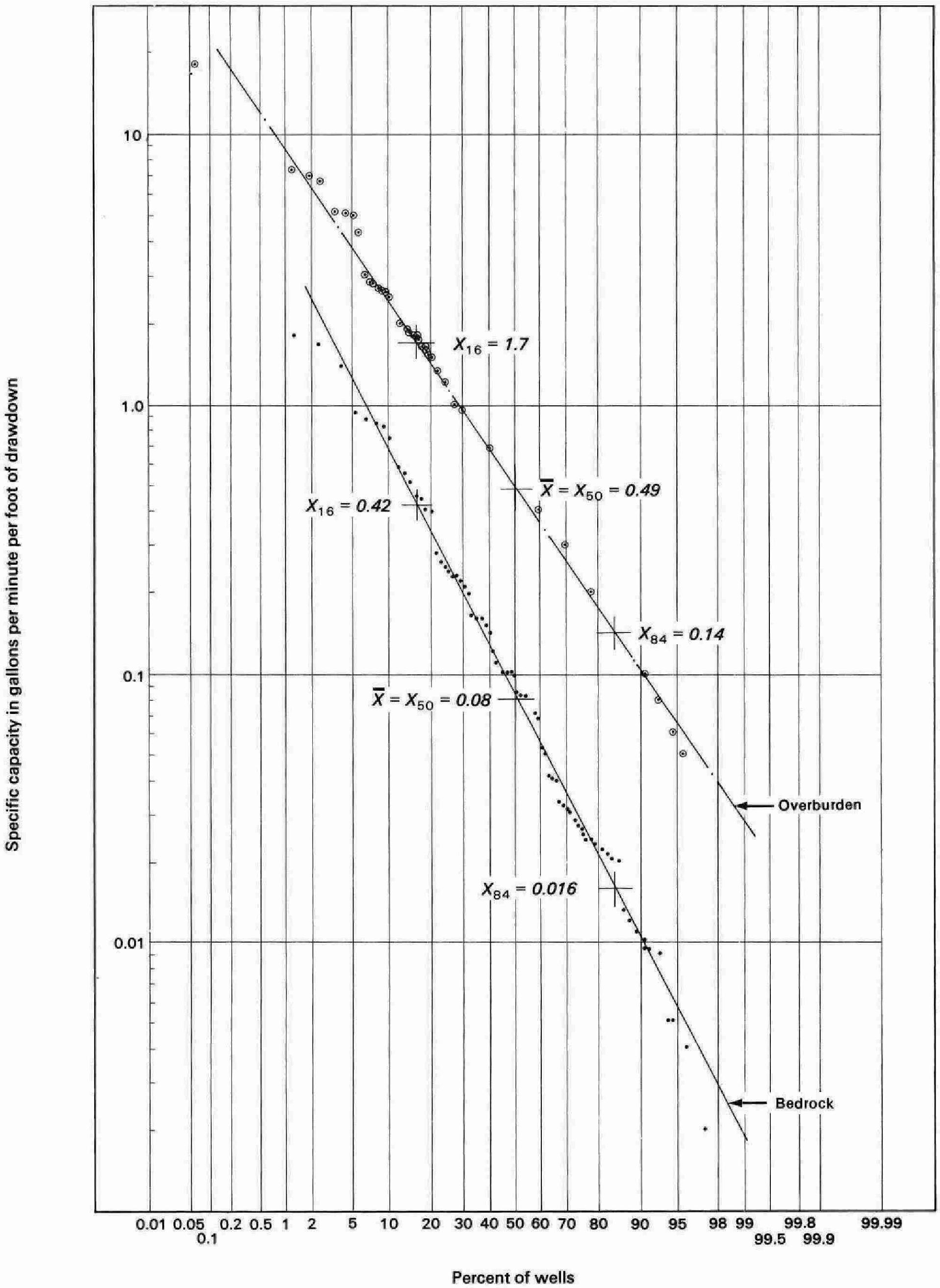

Figure 17. Relation between specific capacities of wells completed in the overburden and in the bedrock.

BASEFLOW ANALYSIS

It is recognized that streamflow consists of the following three components:

(i) Direct runoff which is that part of the precipitation that flows over the land surface to the stream.

(ii) Interflow which is that part of the precipitation that flows part of the way underground, but does not become part of the ground-water body.

(iii) Baseflow which is that part of the precipitation which reaches the streams as natural ground-water discharge, after being a part of the ground-water body.

The amount of baseflow is indicative of the hydrogeologic constants of the aquifers in a basin. Baseflow analysis can be used, as shown by Meyboom (1961), to estimate the total potential ground-water discharge, and the amount of ground-water recharge. The estimated daily average ground-water discharge can also be used to arrive at an approximate average of the transmissibility value for the saturated deposits in a basin.

Millet (1903) (as reported by F. C. Hall, 1968) and Horton (1935) independently developed an equation to compute the recession curve of streamflow hydrographs during periods of drought, which has the form:

$$Q_t = Q_o e^{-\alpha t} \qquad (20)$$

where: Q_o = the discharge at any time,
Q_t = the discharge after time t,
t = the time interval between Q_o and Q_t,
α = the recession constant.

Barnes (1939) proposed the following formula:

$$Q_t = Q_o K_r^t \qquad (21)$$

where K_r = the recession factor, and all the other terms are the same as in Equation 20.

By comparing equations 20 and 21, it follows that:

$$K_r = e^{-\alpha} \qquad (22)$$

and

$$\alpha = \log_e K_r \qquad (23)$$

Three methods have been proposed to determine the baseflow recession constant. These methods are:

(i) The envelope curve by Langbein (1940) on which Q_t is plotted against Q_{t-1} during recession periods.

(ii) The composite curve by Linsley, Kohler and Paulhus (1958) who connected the tails of recession curves together.

(iii) The minimum discharge curve by Meyboom (1961) who drew straight lines connecting successive points of minimum streamflow discharge and considered them to approach true baseflow conditions.

The streamflow hydrographs of the Wilmot Creek for the period 1966-1972 and of the Bowmanville Creek for the periods 1966-1968 and 1970-1972 were analyzed. Values of $_t$ were plotted against values of Q_{t-1} during recession periods (i.e. no rain) and recession constants were determined. the results of this analysis are given in Table 15.

Table 15. Recession Constants of the Bowmanville and Wilmot Creeks

Stream	Station	Kr	a
Bowmanville Creek	02HD006	0.986	0.01410
Wilmot Creek	02HD009	0.985	0.01511

The streamflow hydrographs for the Bowmanville and Wilmot creeks were separated by the following method. Streamflow hydrographs were plotted on semilogarithmic paper and computer plots of these hydrographs were obtained from the Water Survey of Canada. For an isolated storm event, the streamflow recession curve was extended from point A (A is located at the base of the rising limb of the hydrograph) along a line that follows the average recession constant to point B beneath the peak, and then along a straight line from point B to point C.

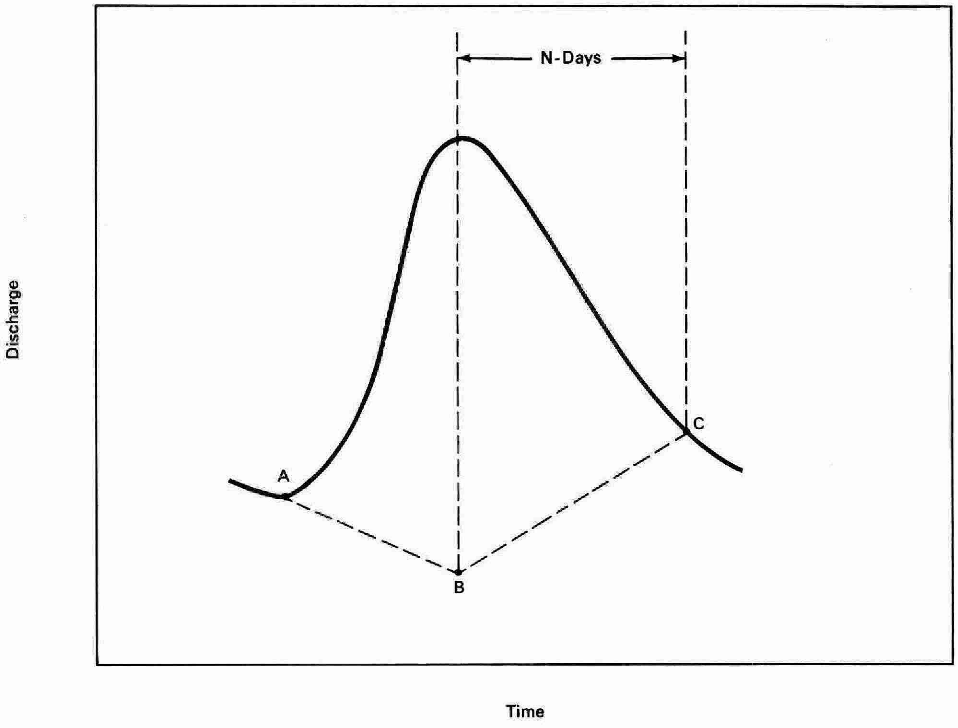

Figure 18. Base-flow separation (after Gray, 1970).

C is the reflection point where the slope of the falling limb of the hydrograph changes (Figure 18). If point C is not well defined, its position is determined using an empirical equation defining N, the number of days after the peak at which direct runoff essentially ends. Lindsley et al (1958) approximate N by the following equation:

$$N = A^{0.2} \tag{24}$$

where: N = the number of days,
A = the drainage area in square miles.

The value of N was found to range from 1 to 3 days by inspecting the hydrographs of both the Bowmanville and Wilmot creeks, whereas, it is computed to be equal to approximately 2 days for both creeks from Equation 24.

Complex hydrographs caused by two or more closely spaced rainfall events were encountered quite often. Figure 19 illustrates the method used for the separation of such complex hydrographs, as described by Gray (1970). The small recession between the peaks is reconstructed from point A to point B which is N days after the occurrence of the first peak. Points E and C are situated beneath the first and the second peaks, respectively, and their positions are determined by extending straight lines from points F and B, following the average recession constant. The line F-E-B-C-D is considered to represent the baseflow hydrograph.

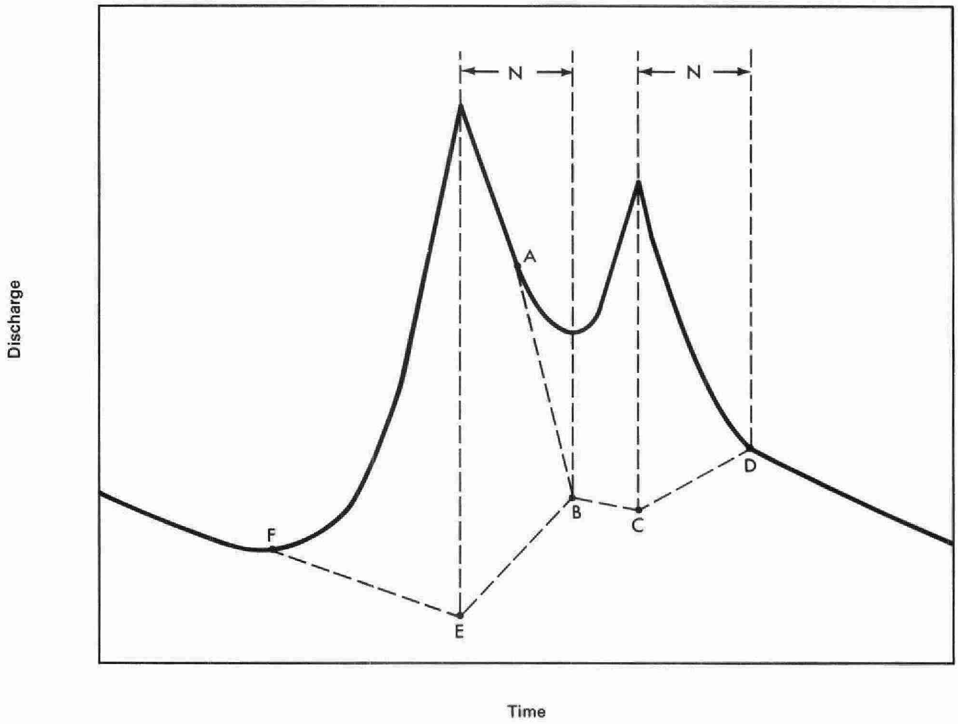

Figure 19. Separation of complex hydrograph (after Gray, 1970).

The methods described for separating streamflow hydrographs are somewhat arbitrary and artificial; however, they are employed consistently throughout this study. Monthly and annual means of ground-water discharges in the Bowmanville and Wilmot creeks are given in tables 16 and 17, respectively.

Table 16. Monthly and Annual means of Ground-Water Discharge for the Bowmanville Creek Basin for the Period 1966-1968 and 1970-1972

Month	1966-1967	1967-1968	1970-1971	1971-1972	Long-Term Monthly Mean
Oct	16.66	23.57	18.18	21.11	19.18
Nov	18.37	27.03	26.00	27.19	24.65
Dec	28.80	26.06	27.93	28.90	27.92
Jan	27.00	29.73	20.78	29.75	26.82
Feb	19.58	33.83	26.02	23.07	25.63
Mar	17.63	36.94	26.20	26.90	26.92
Apr	27.00	29.24	33.37	33.34	30.74
May	23.27	26.23	23.05	19.42	22.99
Jun	19.49	22.70	22.04	16.27	20.13
Jul	20.64	18.08	21.18	18.21	19.53
Aug	18.37	16.75	16.32	22.11	18.39
Sep	17.79	17.70	15.74	22.03	18.32
Annual Mean	21.19	25.66	23.07	24.03	

Area of the basin = 33.39 sq. miles
Long-term, mean ground-water discharge = 23.4 cfs.
Long-term, mean ground-water discharge per unit area = 23.4/33.39 = 0.70 cfs/sq. mi.
Long-term, mean ground-water discharge during the summer and fall months (June-November) = 20.0 cfs.
Long-term, mean ground-water discharge during the winter and spring months (December-May) = 26.8 cfs.

Table 17. Monthly and Annual Means of Ground-Water Discharge for the Wilmot Creek Basin for the period 1966-1972

Month	1966-1967	1967-1968	1968-1969	1969-1970	1970-1971	1971-1972	Long Term Monthly Mean
Oct	12.97	17.50	13.13	16.30	16.25	16.78	15.48
Nov	15.27	22.59	18.23	20.51	19.75	18.13	19.08
Dec	16.02	22.95	21.48	21.65	19.67	19.33	20.10
Jan	15.70	19.40	19.84	16.93	15.79	20.04	17.95
Feb	13.35	24.40	21.91	16.83	17.85	21.49	19.30
March	15.95	25.17	21.04	17.70	27.42	22.20	21.58
April	25.09	27.21	24.27	21.22	31.31	24.42	25.58
May	21.71	21.00	20.93	22.00	21.74	20.39	21.29
June	17.47	15.59	17.18	16.12	15.20	15.46	16.17
July	16.96	11.56	12.36	14.73	13.95	13.96	13.92
Aug	14.96	10.85	14.04	12.31	11.24	15.17	13.09
Sept	12.55	11.56	13.65	13.55	14.49	14.09	13.31
Annual Mean	16.50	19.16	18.16	17.50	18.66	18.41	

Area of the basin = 31.43 sq. miles
Long-term, mean ground-water discharge = 18.0 cfs
Long-term, mean ground-water discharge per unit area = 18.0/31.43 = 0.57 cfs/sq. mi.
Long-term, mean ground-water discharge during the summer and fall months (June-November) = 15.1 cfs
Long-term, mean ground-water discharge during the winter and spring months (December-May) = 20.9 cfs

It is estimated that the long-term, mean ground-water discharge in the Bowmanville Creek is 0.70 cfs per square mile which is equivalent to 9.55 inches of average, annual ground-water discharge. During the summer and fall months (June to November) the ground-water discharge in the Bowmanville watershed averages 0.60 cfs per square mile, whereas, it averages 0.80 cfs per square mile during the winter and spring months (December to May). The

long-term, mean ground-water discharge in Wilmot Creek is 0.57 cfs per square mile which is equivalent to 7.84 inches of annual ground-water discharge. The ground-water discharge within this basin averages 0.48 cfs per square mile during the period June to November and 0.66 cfs per square mile during the period December to May.

Table 18 gives the values of the components of the annual hydrologic budget in the Wilmot Creek basin for the period 1966-1972. The table indicates that the mean annual baseflow constitutes approximately 58 percent of the total runoff and 23 percent of the precipitation over the 6-year period. Assuming that the change in storage during this time period is negligible, the estimated mean annual discharge of 7.84 inches can be considered to approximate the mean annual recharge. Similarly, the mean annual losses of 19.92 inches (losses = evapotranspiration ± change in storage) will approximate the mean annual evapotranspiration.

The mean monthly temperatures recorded at Orono station (Table 19) for the period 1967-1972 were used to estimate the monthly and annual potential evapotranspiration using the Thornthwaite method (Thornthwaite, 1948). The results are given in Table 20 which shows that the average annual potential evapotranspiration at Orono station equals 22.23 inches.

Actual evapotranspiration on a monthly basis was estimated using the Holmes and Robertson moisture budget technique for an assumed soil moisture capacity of 6 inches (Holmes and Robertson, 1960). The results as given in Table 21 indicate that the 6-year average actual evapotranspiration is estimated to be 19.75 inches, which compares favourably with the estimated value of evapotranspiration of 19.92 inches given in Table 18.

Table 18. Estimated Annual Hydrologic Budget of the Wilmot Creek for the Period 1966-1972

Water-Year	Precipitation (inches)	Total Runoff (inches)	Est. Baseflow (inches)	Baseflow as % of total runoff	Baseflow as % of precipitation	Losses = Evapotrans. ± change in storage (inches)
1966-1967	39.59	13.77	7.15	51.92	18.06	25.82
1967-1968	30.55	14.29	8.27	57.87	27.07	16.26
1968-1969	31.92	13.41	7.85	58.53	24.59	18.51
1969-1970	30.19	11.92	7.57	63.50	25.07	18.27
1970-1971	32.54	12.74	8.27	64.91	25.41	19.80
1971-1972	35.42	14.58	7.97	54.60	22.50	20.84
Mean	33.37	13.45	7.84	58.33	23.49	19.92

Normal annual precipitation as recorded at Orono station = 34.20 inches

Table 19. Mean Monthly Temperatures at Orono, Wilmot Creek Basin, 1967-1972

(all values in °F)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1967	25.60	16.30	28.10	40.50	46.10	66.70	66.50	65.70	59.00	48.00	33.60	28.50
1968	16.30	17.40	32.20	45.70	51.80	62.40	68.00	66.30	62.40	49.90	35.90	22.10
1969	20.50	23.90	27.40	44.30	52.20	60.70	67.80	69.00	59.20	46.80	38.20	21.00
1970	12.40	18.20	27.20	44.30	53.40	61.90	68.40	67.90	59.10	50.60	38.70	20.20
1971	15.20	22.60	25.40	39.20	51.50	61.80	63.80	65.20	61.40	53.90	33.30	27.70
1972	20.40	17.30	24.70	37.00	54.60	59.60	66.70	64.20	59.40	42.00	33.00	24.70

Table 20. Estimated Monthly and Annual Potential Evapotranspiration at Orono, Wilmot Creek Basin, Based on Thornthwaite Method

(all values in inches)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1967	0.0	0.0	0.0	1.00	1.88	4.79	4.84	4.39	3.08	1.66	0.13	0.0	21.77
1968	0.0	0.0	0.01	1.54	2.56	4.09	4.99	4.40	3.40	1.77	0.30	0.0	23.07
1969	0.0	0.0	0.0	1.40	2.65	3.88	4.99	4.80	3.05	1.48	0.51	0.0	22.76
1970	0.0	0.0	0.0	1.36	2.77	4.02	5.05	4.62	3.00	1.85	0.53	0.0	23.20
1971	0.0	0.0	0.0	0.83	2.61	4.08	4.44	4.31	3.35	2.28	0.10	0.0	21.99
1972	0.0	0.0	0.0	0.62	3.13	3.85	4.92	4.24	3.18	1.08	0.09	0.0	21.13

Estimated long-term, mean potential evapotranspiration = 22.32 inches

Table 21. Estimated Mean Monthly and Annual Actual Evapotranspiration at Orono, Wilmot Creek Basin, Based on Holmes and Robertson Moisture Budget Technique

(all values in inches)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1967	0.0	0.0	0.0	1.00	1.88	4.79	4.84	3.70	3.00	1.66	0.13	0.0	21.00
1968	0.0	0.0	0.01	1.54	2.56	4.09	2.53	2.88	2.51	1.77	0.30	0.0	18.19
1969	0.0	0.0	0.0	1.40	2.65	3.88	4.75	3.38	0.79	1.48	0.51	0.0	18.85
1970	0.0	0.0	0.0	1.36	2.77	4.02	4.94	3.35	1.86	1.85	0.53	0.0	20.68
1971	0.0	0.0	0.0	0.83	2.61	4.08	4.21	3.15	1.96	2.20	0.10	0.0	19.14
1972	0.0	0.0	0.0	0.62	3.13	3.80	4.56	4.24	3.09	1.08	0.09	0.0	20.62

Estimated long-term, mean annual actual evapotranspiration = 19.75 inches

ESTIMATION OF THE AMOUNT OF GROUND-WATER DISCHARGE INTO LAKE ONTARIO

The main objective of this study was to determine the amount of ground-water flow into Lake Ontario. Two methods were applied to solve this problem; baseflow analysis and Darcy's Law.

THE FIRST METHOD

The first method is based on the assumption that the direct ground-water discharge per unit area of the catchment along the shoreline of Lake Ontario is equal to the average ground-water discharge per unit area of the Bowmanville and Wilmot creeks watersheds. This assumption implies that the geology within the catchment area along the Lake Ontario shoreline is similar to that within the above-mentioned watersheds and is valid if only the order of magnitude of the ground-water discharge into the lake is required.

The area of the catchment that discharges ground water directly into Lake Ontario may vary considerably from 2.29 square miles if the area of small watersheds along the shoreline is excluded, up to 12.15 square miles if this area is included. In general, when the ground-water levels rise (winter and spring) the streams in these watersheds are active with the ground water discharging into them as baseflow. Under these conditions the area of the catchment that discharges directly to Lake Ontario reduces to 2.29 square miles. On the other hand, when the ground-water levels drop (summer and fall) the baseflow into these streams diminishes to almost nothing with most of the ground water discharging directly to the lake as underflow from these watersheds. The area of the catchment that discharges ground water directly to the lake will increase in this case up to 12.15 square miles. The average baseflow per unit area for the Bowmanville and Wilmot creeks watershed was estimated to vary from 0.54 cfs/sq. mile for the summer and fall period to 0.73 cfs/sq. mile for the winter and spring period.

By applying this method, two values are given for the amount of direct ground-water discharge into Lake Ontario. The first value is for the winter and spring period and it equals 1.67 cfs which is equivalent to 0.12 cfs per mile length of the shoreline. The second value is for the summer and fall period and it equals 6.56 cfs which is equivalent to 0.44 cfs per mile length of the shoreline. It is recognized that both these values are rough estimates, but it is thought that the true value lies between them.

THE SECOND METHOD

This method is based on Darcy's Law:

$$Q = T\,I\,L \tag{25}$$

where: Q = the ground-water discharge into Lake Ontario, in IGPM,
T = the average transmissibility of the water-bearing formations in IGPM/ft.,
I = the hydraulic gradient obtained from water wells located along the shoreline, dimensionless,
L = the length of the shoreline, in feet.

The hydraulic gradient obtained from the water wells located along the shoreline ranges from 0.001 to 0.021 with an average value of 0.011. The length of the shoreline equals 14 miles or 73,920 feet. Two estimates are available for the transmissibility of the water-bearing deposits along the shoreline. These estimates are about 1800 IGPD/ft. or 1.25 IGPM/ft. and 1300 IGPD/ft. or 0.90 IGPM/ft. The first estimate is based on the assumption that the transmissibility of the deposits along the Lake Ontario shoreline is equal to the average transmissibility value obtained from pumping and recovery tests, whereas the second estimate is based on the assumption that the transmissibility of these deposits is equal to the average transmissibility value obtained from baseflow analyses of Bowmanville and Wilmot streamflows.

Based on the above two estimates of the transmissibility of the shoreline deposits, it is possible to compute two values for the amount of ground-water discharge into Lake Ontario by applying Darcy's Law. These values are 1016 IGPM or 2.75 cfs and 732 IGPM or 1.96 cfs for the first and second transmissibility estimates respectively which are equivalent to 0.19 cfs and 0.14 cfs of ground-water discharge per mile length of the shoreline.

In summary, four values of ground-water inflow to Lake Ontario within the Bowmanville-Newcastle area were obtained; 6.56 cfs and 1.67 cfs based on the *first method*, and 2.75 cfs and 1.96 cfs based on the *second method*, which are equivalent to 0.44 cfs, 0.12 cfs, 0.19 cfs and 0.14 cfs of ground-water discharge per mile length of the shoreline.

As was previously indicated, the study area is considered to be representative of the ground-water regime developed in a hydrogeologic region extending from Oshawa to the Trent River, which extends approximately 70 miles along the shoreline of Lake Ontario. Four values are represented here for the amount of ground-water inflow into Lake Ontario within this region. These values are 30.80 cfs, 8.40 cfs, 13.30 cfs and 9.80 cfs and were obtained from extrapolating the ground-water discharge per mile length of the shoreline with the Bowmanville-Newcastle representative area to the Oshawa-Trent River region. The first and second values (30.80 cfs and 8.40 cfs), represent the ground-water discharge into the lake during the summer-fall and winter-spring periods respectively, as computed from the *first method*. The third and fourth values (13.30 cfs and 9.80 cfs) represent the ground-water discharge into the lake as computed from the *second method*.

The representative area extending from Oshawa to the Trent River is approximately equivalent to area "c" which was considered by Haefeli in his report on ground-water inflows into Lake Ontario from the Canadian side (Haefeli, 1972). Haefeli gave three different values for the amount of ground-water inflow into Lake Ontario within area "c". These values are 38.7 cfs, 13.34 cfs and 8.19 cfs. The first value given by Haefeli was obtained by extrapolating the baseflow per unit area of the large watersheds within area "c" to the shore catchment discharging directly into Lake Ontario. The catchment area that was considered by Haefeli included all the small watersheds discharging into Lake Ontario within area "c" as the estimate was made for the summer period only. The two other values for the ground-water discharge into Lake Ontario given by Haefeli are based on the application of Darcy's Law. The transmissibility value that was used to obtain the second value was derived from specific capacity data of water wells situated in the shore belt within area "c", whereas the transmissibility value used to obtain the third value was derived from baseflow analyses.

Table 22 gives a comparison between the estimates of ground-water discharge into Lake Ontario as obtained in this study for the Bowmanville-Newcastle area and the Oshawa-Trent River region and those estimates given by Haefeli (1972) for area "c". The comparison indicates good agreement.

Table 22. Comparison of the Estimates of Ground-Water Inflow into Lake Ontario Using Various Methods

(all values in cfs)

Method	Estimated ground-water inflow into L. Ontario within the Bowmanville-Newcastle area	Estimated ground-water inflow into L. Ontario per mile length of the shoreline in the Bowmanville-Newcastle area	Estimated ground-water inflow into L. Ontario within the Oshawa-Trent River region	Estimated ground-water inflow into L. Ontario within area "c" as reported by Haefeli (1972)
a. Extrapolating the baseflow per unit in the Bowmanville and Wilmot creeks basin to the shore catchment	6.56 (summer period) 1.67 (winter period)	0.44 (summer period) 0.12 (winter period)	30.80 (summer period) 8.40 (winter period)	38.70 (summer period) —
b. Darcy's Law	2.75 1.96	0.19 0.14	13.30 9.80	13.34 8.19

SUMMARY AND CONCLUSIONS

1. The hydrogeologic regime of an area bounded on the south by the present-day shore of Lake Ontario and on the north by the abandoned Lake Iroquois shoreline and extending east and west beyond the watershed divide of the Bowmanville, Soper and Wilmot creeks drainage basin was studied as a part of the IFYGL program. The selected area is considered to be representative of a larger hydrogeologic region extending approximately 70 miles from Oshawa to the Trent River.

2. The selected study area is a part of the Iroquois Plain which is made up of ground moraine that was modified by the action of glacial Lake Iroquois. A detailed examination of the surficial geology along the present-day shore of Lake Ontario within the study area revealed the presence of glacial, glacio-lacustrine and glacio-fluvial deposits which rise as bluffs above lake level. The basal unit is a dense, clay-silt till, overlain by up to 65 feet of varved clay and stratified sand. A middle till of limited lateral extent was identified. Lithologically, it is similar to the basal till and is overlain by an upper sand till which outcrops at surface. The upper till generally consists of two units separated by sandy silt deposits up to 45 feet in thickness. Where the relief is low, a mantle of varved clay representing deposition in a proglacial lake is found at surface.

Correlation with the surficial deposits found to the east of Toronto indicates that the deposits in the study area are Wisconsinan in age.

3. The bedrock in the study area is obscured by overlying deposits of glacial drift. Black shales of the Whitby Formation are present in the western part of the study area while dark, bituminous limestones subcrop throughout the rest of the area.

4. Ground water occurs in fissures, joints and bedding planes of the bedrock formations and in the pore spaces between grains of silt, sand and gravel or stone fragments within the overburden.

5. The availability of ground water within the bedrock is controlled by the distribution of the water-yielding openings and within the overburden by the type and thickness of deposits. In general, wells completed in the bedrock are suitable to supply domestic requirements only. The ground-water availability in the overburden deposits ranges from poor to good. Locally, overburden deposits are the most productive sources of ground water within the study area.

6. The ground-water level fluctuations vary from 0.96 to 11.1 feet and the largest rise in ground-water levels occurs during the months of April and May which coincide with the snow-melt period.

7. The permeability and transmissibility of various types of deposits was determined using the following methods:

(a) pumping and recovery tests,

(b) grain-size distributions obtained from mechanical analyses,

(c) baseflow analysis.

The average transmissibility of the overburden and the upper 50 feet of the bedrock was estimated to be equal to about 1800 IGPD/ft. based on pumping and recovery tests results. Based on baseflow analyses, the average transmissibility of the overburden deposits was estimated to be equal to about 1300 IGPD/ft. for the Bowmanville Creek and for the Wilmot Creek basins.

8. A comparison between the specific capacity frequency graphs for the overburden and the bedrock indicates that the productivity of the overburden deposits is higher than that of the bedrock. At the same time, the bedrock formations are more uniform than the overburden deposits.

9. The monthly and annual ground-water discharges were estimated from baseflow analyses. It was estimated that the mean ground-water discharge in Bowmanville Creek is 0.70 cfs per square mile which is equivalent to 9.55 inches of annual ground-water discharge. For Wilmot Creek, the mean ground-water discharge is 0.57 cfs per square mile which is equivalent to an annual average ground-water discharge of 7.84 inches.

10. The amount of direct ground-water discharge into Lake Ontario was estimated by two different methods;

(a) By extrapolating the average baseflow per unit area in the Bowmanville and Wilmot basins to the shore catchment which discharges directly into Lake Ontario.

(b) By applying Darcy's Law.

Direct ground-water discharge into Lake Ontario within the study area was estimated to vary from 1.67 cfs to 6.56 cfs (method a) and from 1.96 cfs to 2.75 cfs (method b). By extrapolating these results to the Oshawa-Trent River hydrogeologic region, the direct ground-water inflow into Lake Ontario within the limits of this area is estimated to range from 8.4 cfs to 30.8 cfs (method a) and from 9.8 cfs to 13.3 cfs (method b).

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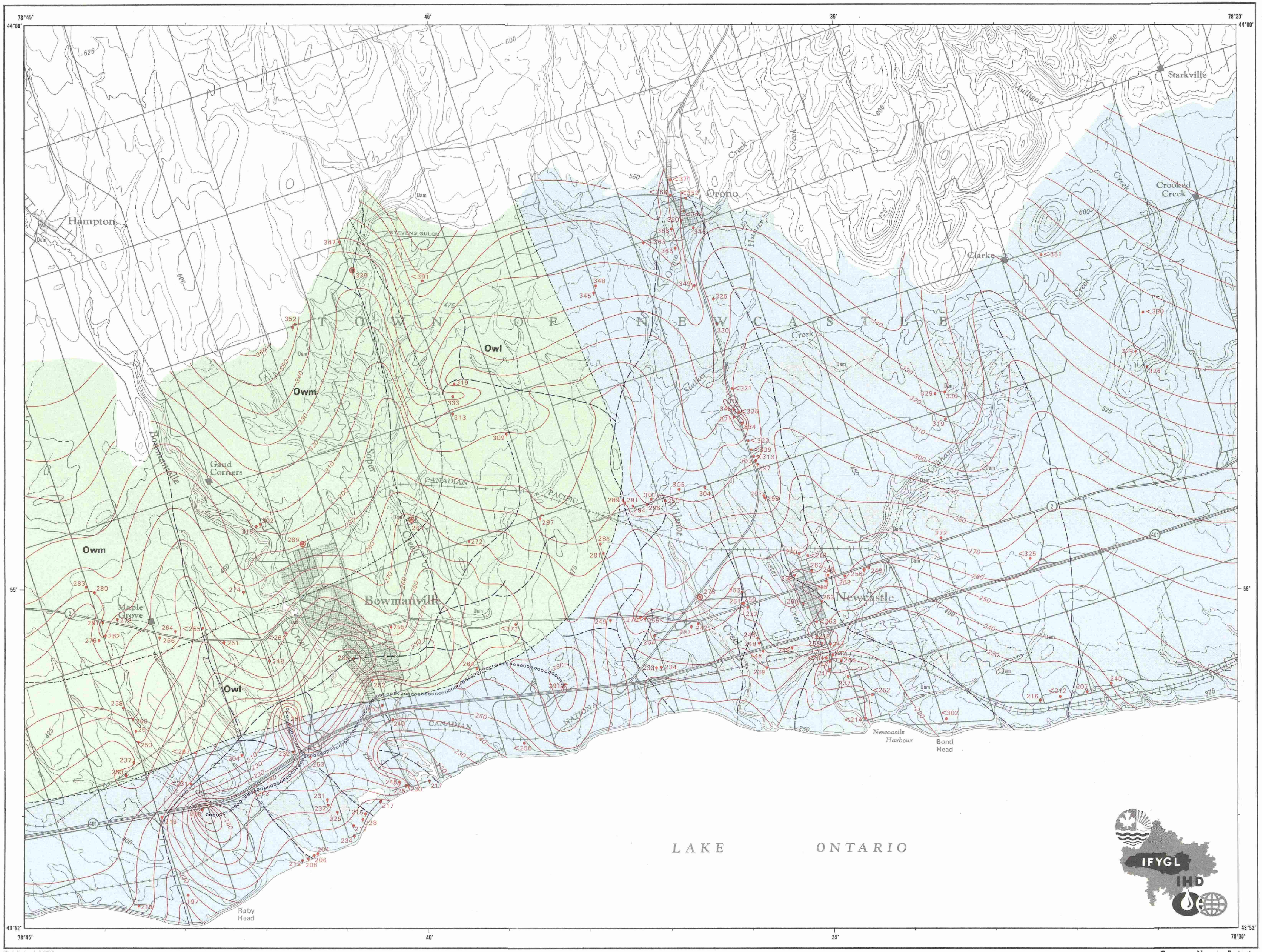

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LEGEND

PALAEOZOIC

UPPER ORDOVICIAN

Whitby Formation
Owm-Middle Member: brown shale
Owl-Lower Member: black shale

UPPER and MIDDLE ORDOVICIAN

Lindsay Formation: grey, very fine-crystalline limestone, claystone

SYMBOLS

- Geological boundary, approximate
- Topographic contour, interval 25 feet
- Bedrock surface contour, interval 10 feet
- Bedrock drainage
- Crest of bedrock
- Water well ending in bedrock
- Water well ending in overburden
- Observation well ending in bedrock
- Flowing well ending in bedrock
- 272 Elevation of bedrock surface

SOURCES OF INFORMATION

Bedrock topography by S. N. Singer, 1973, on the basis of water-well records assembled by the Ministry of the Environment.

Bedrock geology after B. A. Liberty

References:
Liberty, B. A., 1953, Paleozoic geology of the Oshawa area, Ontario; Geol. Surv. Can., Prelim. Map 53-18.
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Cartography by V. Roberts, 1974.

Base map derived from 1:25,000 map sheets of the National Topographic Series.

To accompany Water Resources Report 5d

Ontario

MINISTRY OF THE ENVIRONMENT
Water Quantity Management Branch

Hon. William G. Newman, *Minister*
Everett Biggs, *Deputy Minister*

INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

BOWMANVILLE AREA

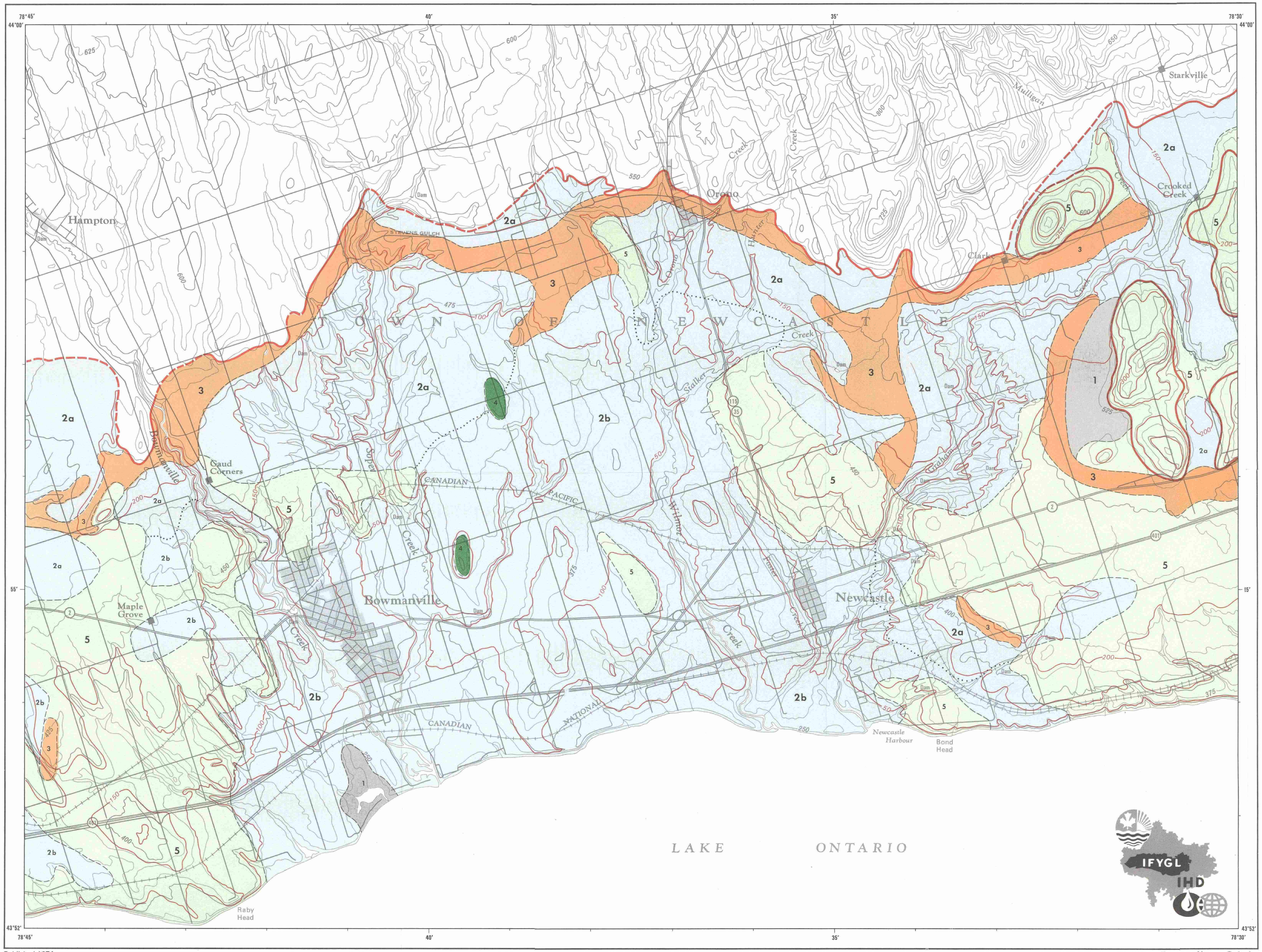
MAP 1

BEDROCK GEOLOGY AND TOPOGRAPHY

Scale 1:50,000
1 inch equals 0.79 miles

0 ½ 1 2
Miles

0 ½ 1 2
Kilometres



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Transverse Mercator Projection

LEGEND

1	**Swamp and muck**
2	**Lake plain:** 2a-sand, 2b-silt and clay
3	**Beach, bar and similar features:** sand, gravel
4	**Drumlin**
5	**Ground moraine:** mainly sandy till

SYMBOLS

- Geological boundary, approximate
- 250 Topographic contour, interval 25 feet
- 300 Line of equal overburden thickness (isopach), interval 50 feet
- Lake Iroquois shoreline; definite, assumed

SOURCES OF INFORMATION

Surficial geology and overburden thickness by S. N. Singer, 1973, on the basis of cited reference and water-well records assembled by the Ministry of the Environment.

Reference:

Gravenor, C. P., 1959, Surficial geology of the Lindsay-Peterborough area, Ontario; Geol. Surv. Can., Map 1050A

Cartography by V. Roberts, 1974.

Base map derived from 1:25,000 map sheets of the National Topographic Series.

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INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

BOWMANVILLE AREA

MAP 2

SURFICIAL GEOLOGY AND OVERBURDEN THICKNESS

Scale 1:50,000

1 inch equals 0.79 miles

0 ½ 1 2
Miles

0 ½ 1 2
Kilometres

MAP 4724-12

LEGEND

Water well

Observation well

Surface-water divide

SOURCES OF INFORMATION

Location of water wells compiled by S. N. Singer, 1973, on the basis of water-well records assembled by the Ministry of the Environment.

Cartography by V. Roberts, 1974.

Base map derived from 1:25,000 map sheets of the National Topographic Series.

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INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

BOWMANVILLE AREA

MAP 3

LOCATION OF WATER WELLS

Scale 1:50,000

1 inch equals 0.79 miles

0 ½ 1 2
Miles

0 ½ 1 2
Kilometres

Published 1974

Transverse Mercator Projection

LEGEND

350	Water-level contour, interval 50 feet
	Water well ending in bedrock
	Water well ending in overburden
	Observation well ending in overburden
	Flowing well ending in bedrock
	Flowing well ending in overburden
273	Water level
	Surface-water divide

SOURCES OF INFORMATION

Water-level contours by S. N. Singer, 1973, on the basis of water-well records assembled by the Ministry of the Environment.

Cartography by V. Roberts, 1974.

Base map derived from 1:25,000 map sheets of the National Topographic Series.

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INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

BOWMANVILLE AREA

MAP 4

WATER LEVEL CONTOURS IN THE OVERBURDEN

Scale 1:50,000

1 inch equals 0.79 miles

0 ½ 1 2
Miles

0 ½ 1 2
Kilometres

MAP 4724-14

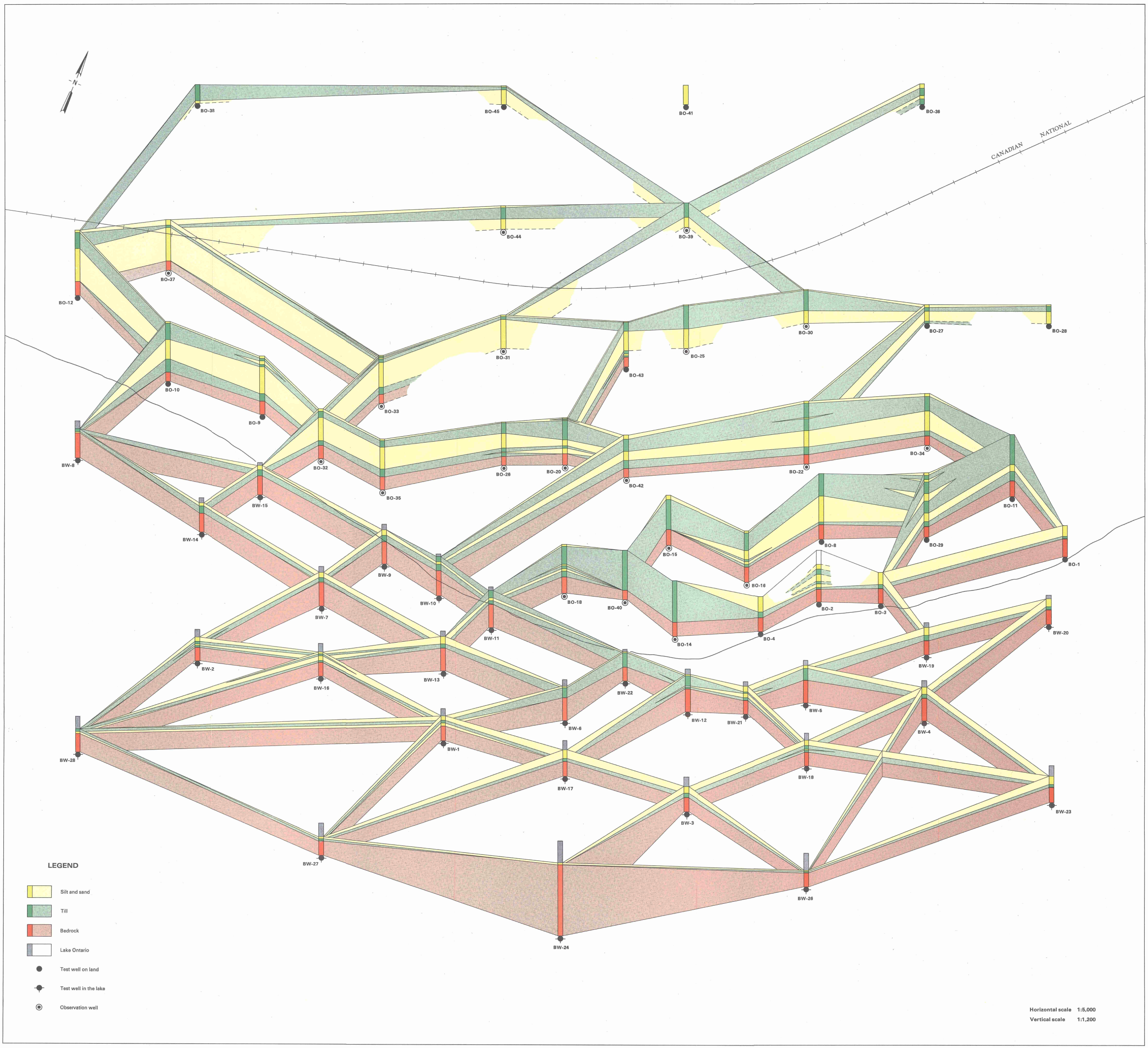

Figure 5. Panel diagram of the subsurface geology at the Raby Head site.